

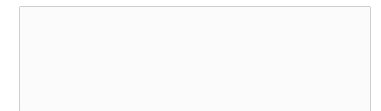
Electroweak and Top Physics at High Energies

Results from Tevatron and Hera with
predictions for LHC
on behalf of



Florencia Canelli

The University of Chicago and Fermilab
Lepton Photon Conference
August, 2009



Hadron Colliders

Hera, Desy



- ▶ 319 GeV proton – electron collider
- ▶ Run 1992-2007
- ▶ Accumulated luminosity $\sim 200 \text{ pb}^{-1}$ in e^-p and $\sim 300 \text{ pb}^{-1}$ in e^+p

Some results

Tevatron, Fermilab



- 1.96 TeV p-anti p collider
- Run II started in 2002
- Has delivered $\sim 7 \text{ fb}^{-1}$ of data since 2002, and running smoothly: expect $\sim 12 \text{ fb}^{-1}$ by end of 2011

Most of the results

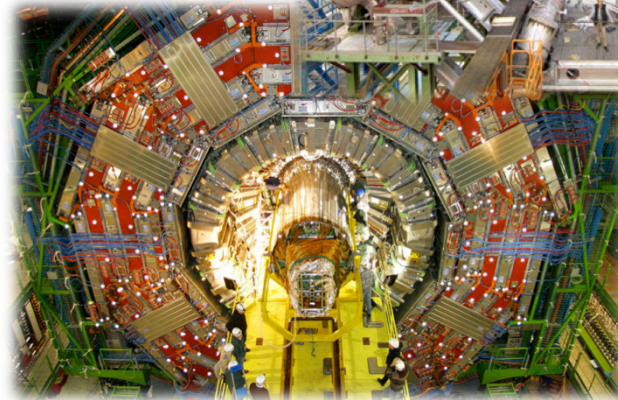
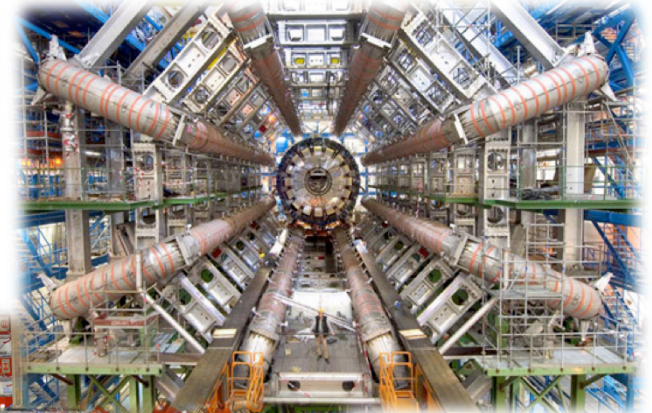
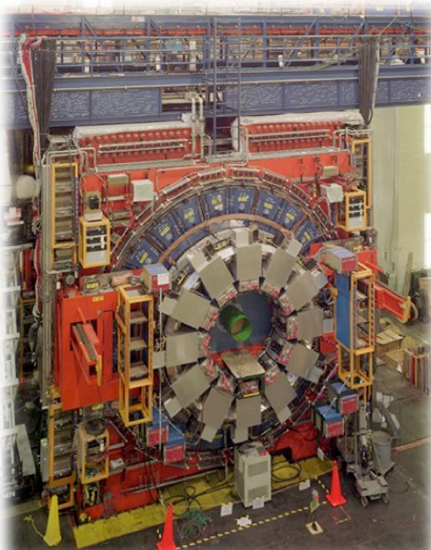
LHC, Cern



- $\leq 14 \text{ TeV}$ p-p collisions
- Expect to turn on late 2009 at 7 TeV
- Expect up to 200 pb^{-1} in the early run

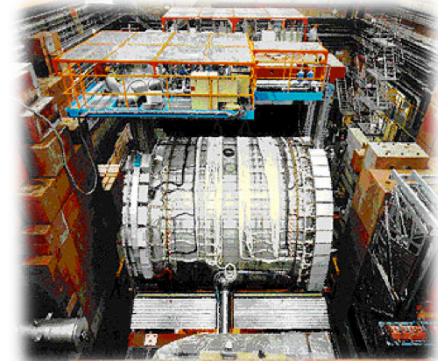
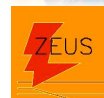
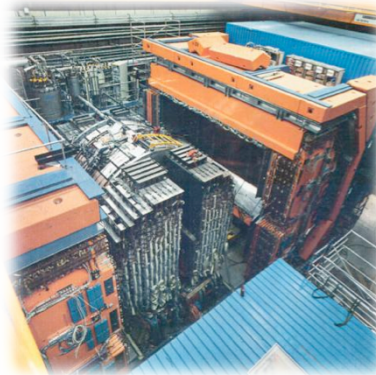
Some prospects

Detecting High-Energy Hadron Collisions



- Similar detectors in hadron collider experiments:

- **Inner trackers**
- **Calorimeters**
- Outer **muon detectors**
- Most measurements in the transverse plane: E_T , P_T , missing E_T



Outline of this Talk

- **Establishing Electroweak and Top quark signatures**
 - W and Z bosons
 - Diboson
 - Top quark pairs
 - Single top quark
- **Standard model constrains using precision measurements**
 - W boson mass and top quark mass
 - Electroweak fit and predictions for Higgs boson
- **Top quark physics**
 - Measurements of properties
 - Searches beyond the standard model

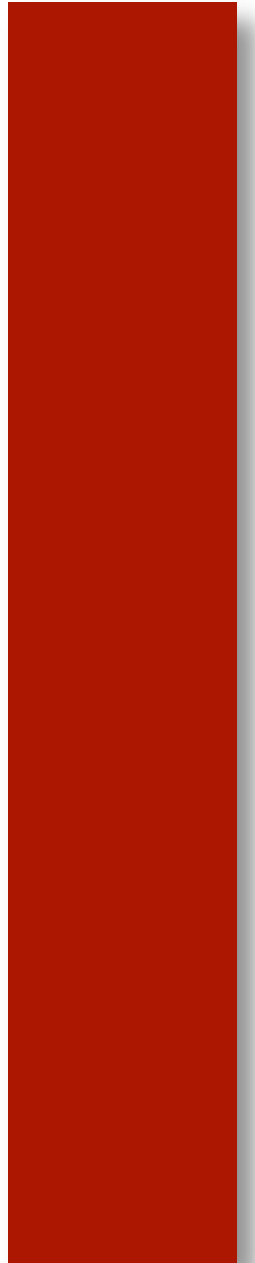
Establishing Signatures

W and Z bosons

Diboson

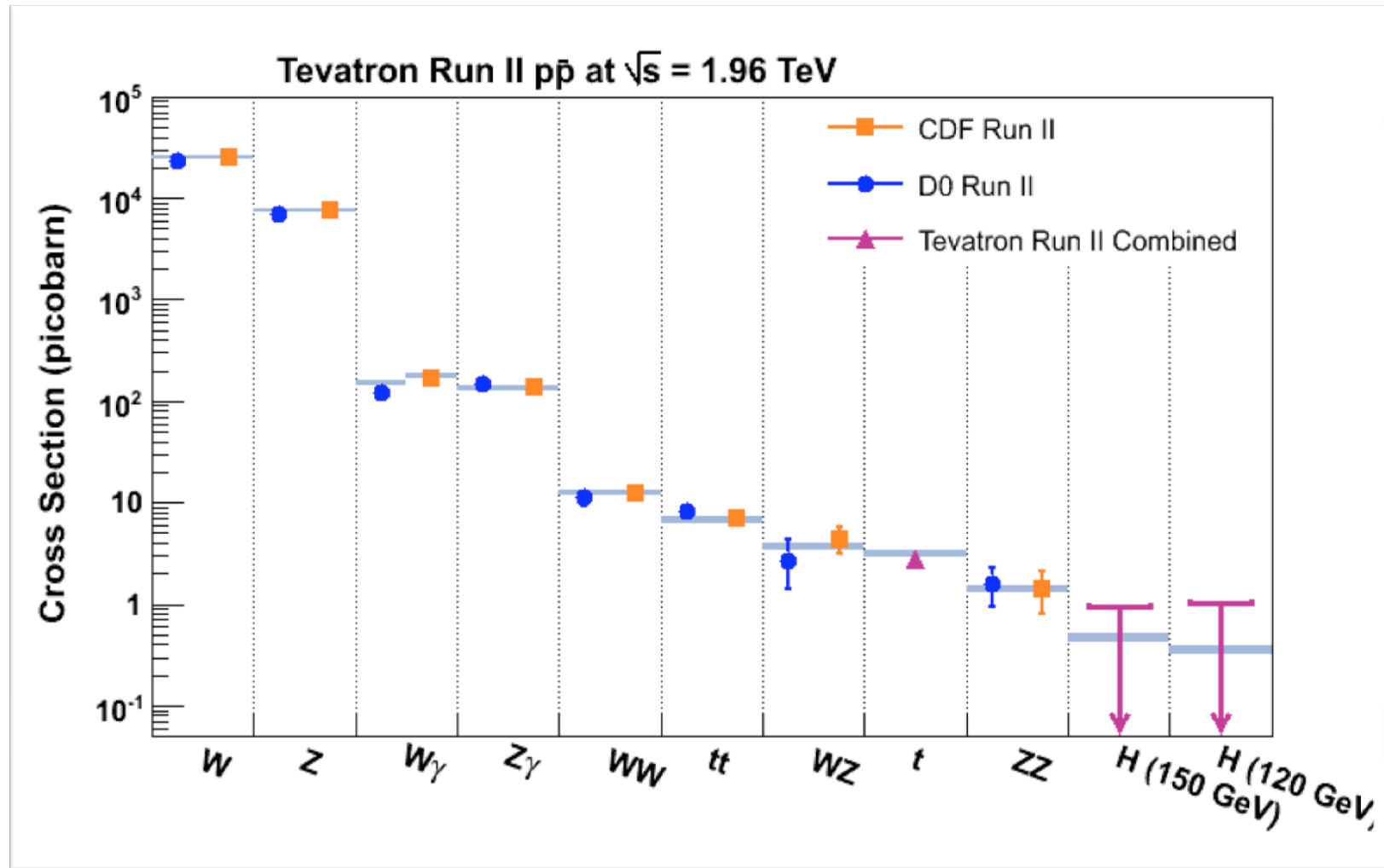
Top quark pairs

Single top quark



Electroweak and Top Samples

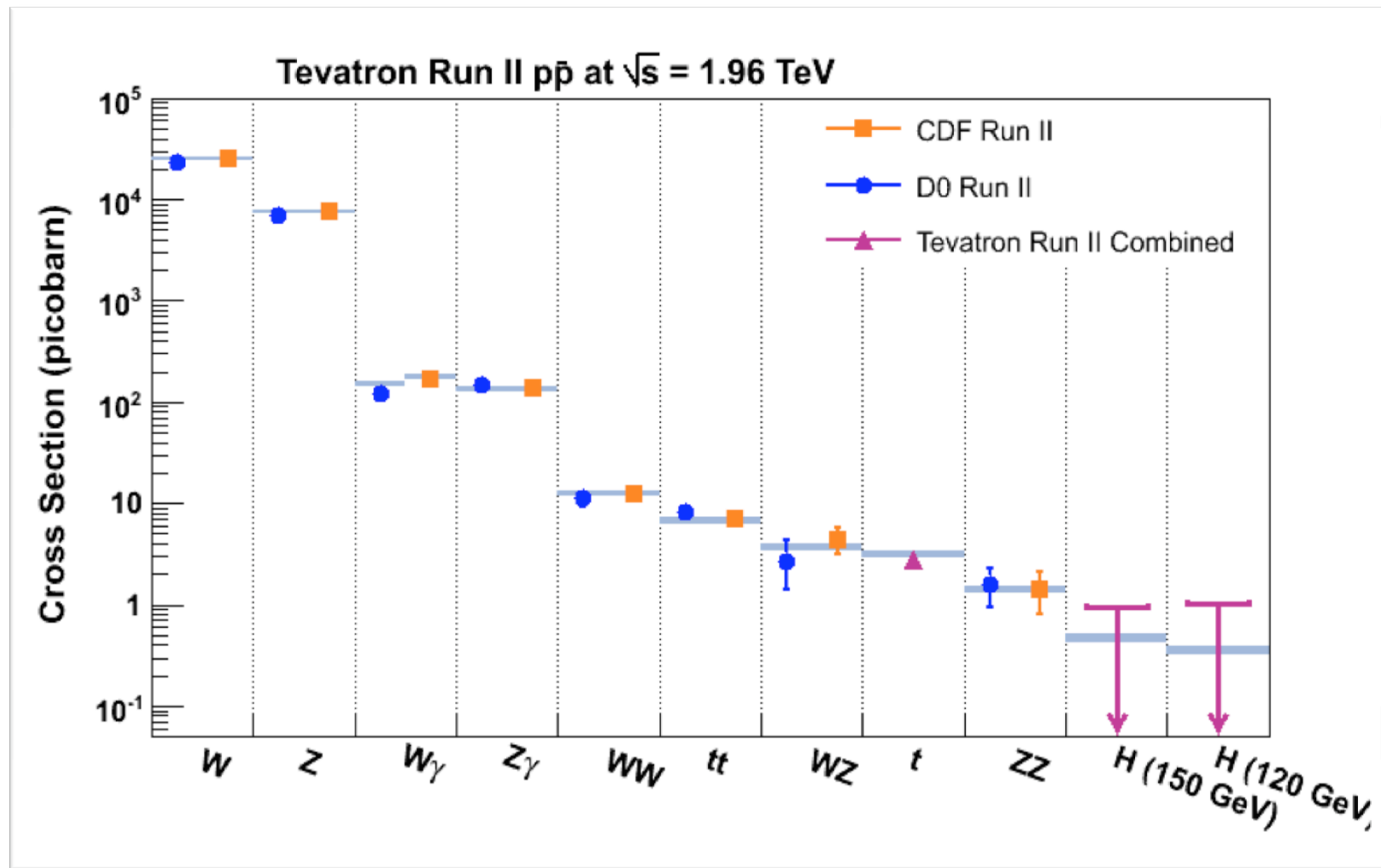
- Span over a wide range of cross sections



- Until the past year only cleaner channels were observed: small background, lower statistics
 $W\gamma \rightarrow l\nu\gamma$ $Z\gamma \rightarrow ll\gamma$ $WW \rightarrow l\nu l\nu$ $WZ \rightarrow l\nu ll$ $ZZ \rightarrow ll ll$

Electroweak and Top Samples

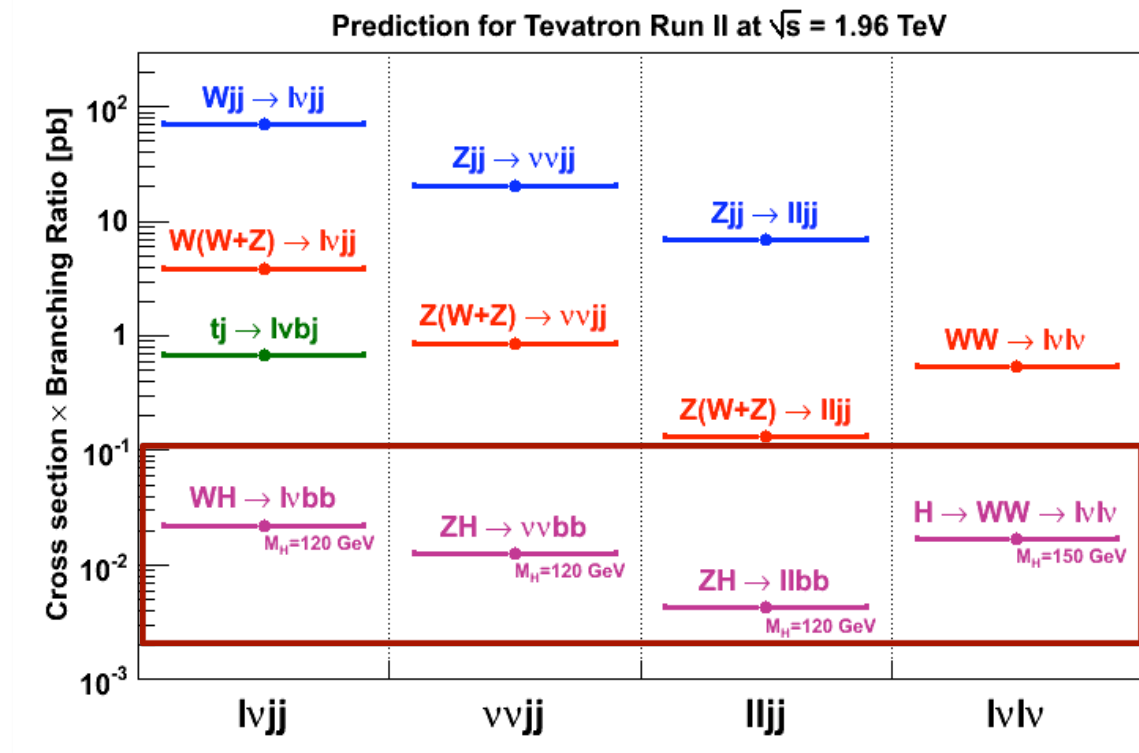
- Span over a wide range of cross sections



New this year: more data + the difficult channels, large backgrounds, no easy kinematic handles $Z\gamma \rightarrow \nu\nu\gamma$ $WW \rightarrow l\nu jj$ $WZ \rightarrow l\nu jj$ $ZZ \rightarrow \nu\nu jj$ Single top $\rightarrow l\nu jj$

Electroweak and Top Quark Physics

- Difficult signatures are interesting because they are **backgrounds in Higgs boson searches**
- Establishing processes in different channels
 - Allow us to **Combine** to improve precision
 - Gives us **Confidence** in different modeling and techniques
 - Establishes **Consistency** among channels
- In general, measuring cross sections:
 - Could point out to **new physics through** deviations from the standard model
 - Establishes samples for making other **measurements** possible



Measurement Techniques

More sophisticated methods are used as the experimental challenges increase (i.e., small S/B, signal and background kinematically similar)

Counting events



Establish selection, estimate expected background

Find number of data events

Subtract expected background data from data events

Templates/Likelihood



Reconstruct the best discriminating variable X (ex. an invariant mass)

Form signal and background templates of X

Perform a maximum likelihood fit between data and templates

Matrix Element



Form per-event probability using matrix elements

Evaluate the probability of each event for signal and background hypotheses

Use probability into one likelihood (discriminant type or as a function of a parameter)

Neural Networks, Boosted Decision Trees



Find good discriminating variables (well modeled in MC)

Input variables from MC to train a multivariate package

Use output as a discriminant, likelihood fit between data and MC

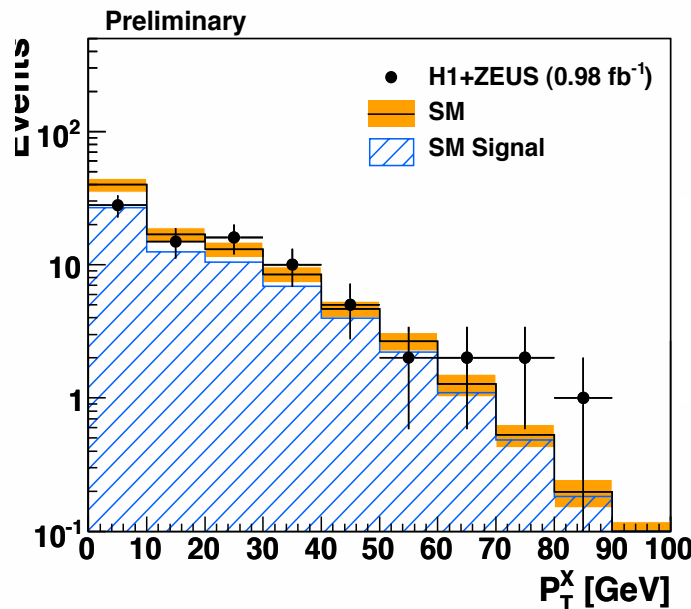
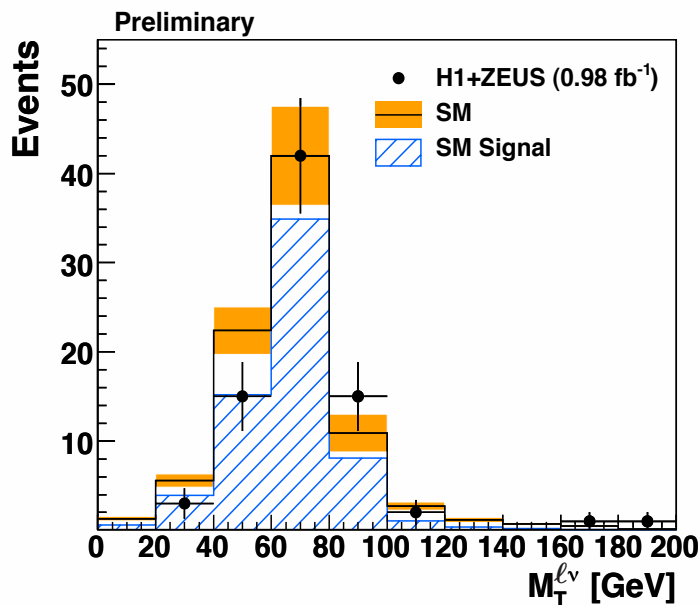
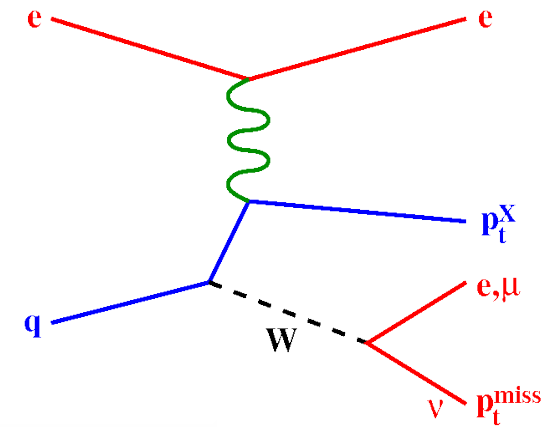
W at Hera

- Standard model prediction for W production at HERA $ep \rightarrow eW^\pm X$
- Striking signature: $\ell=e, \mu$ and ν in the same event, with high p_T
- Could be a signature for new physics
- Previously H1 reported an excess at high p_T^X
- Good agreement found, no excess observed

H1 + ZEUS (0.98 fb⁻¹):

$\sigma_W = 1.07 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}) \text{ pb}$

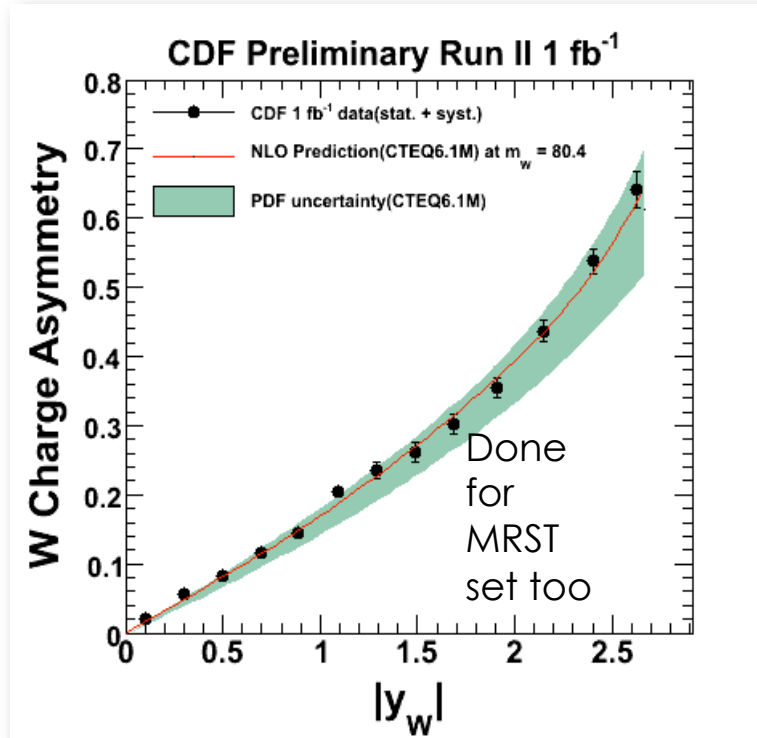
SM prediction
 $\sigma = 1.26 \pm 0.19 \text{ pb}$



At large $p_T^X > 25$
GeV:
e⁺p: 23 / 14.0 ± 1.9
e⁻p: 6 / 10.0 ± 1.3

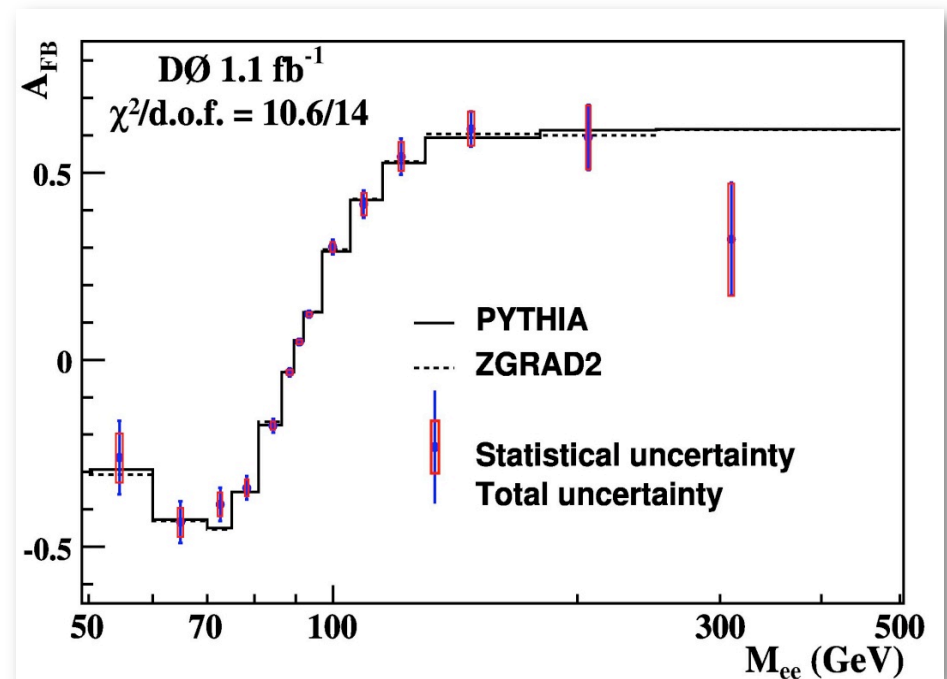
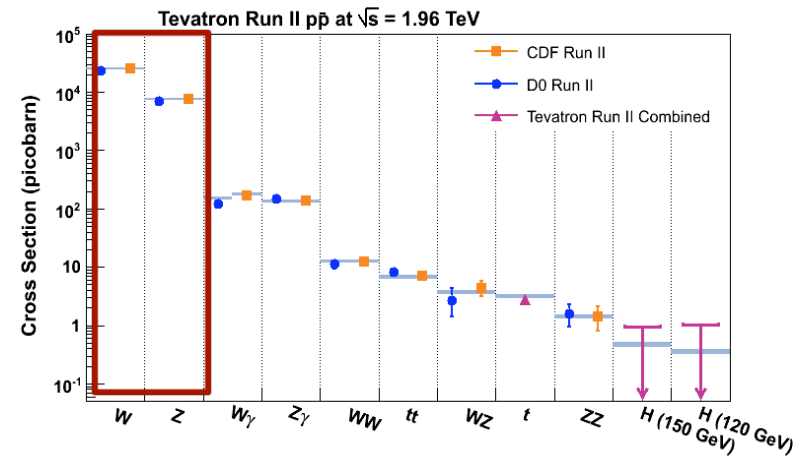
W and Z

- W production **charge asymmetry** expected to constrain PDFs



- Forward-backward asymmetry** measured in $Z/\gamma^* \rightarrow e^+e^-$

- With 8 fb⁻¹ Tevatron can reach a precision comparable to the world average



DØ (1.1 fb⁻¹):
 $\sin^2\theta_w = 0.2326 \pm 0.0018(\text{stat}) \pm 0.006(\text{syst})$

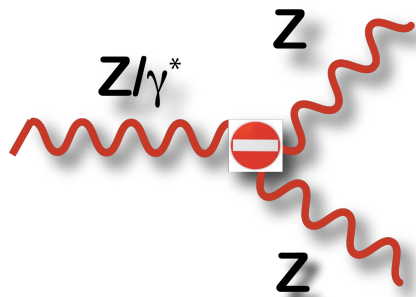
$Z\gamma$

- Observed at the Tevatron with $\sim 3\%$ precision in the $Z\gamma \rightarrow \ell\ell\gamma$ channel - consistent with SM
- First measurement using $Z \rightarrow \nu\nu$ decay

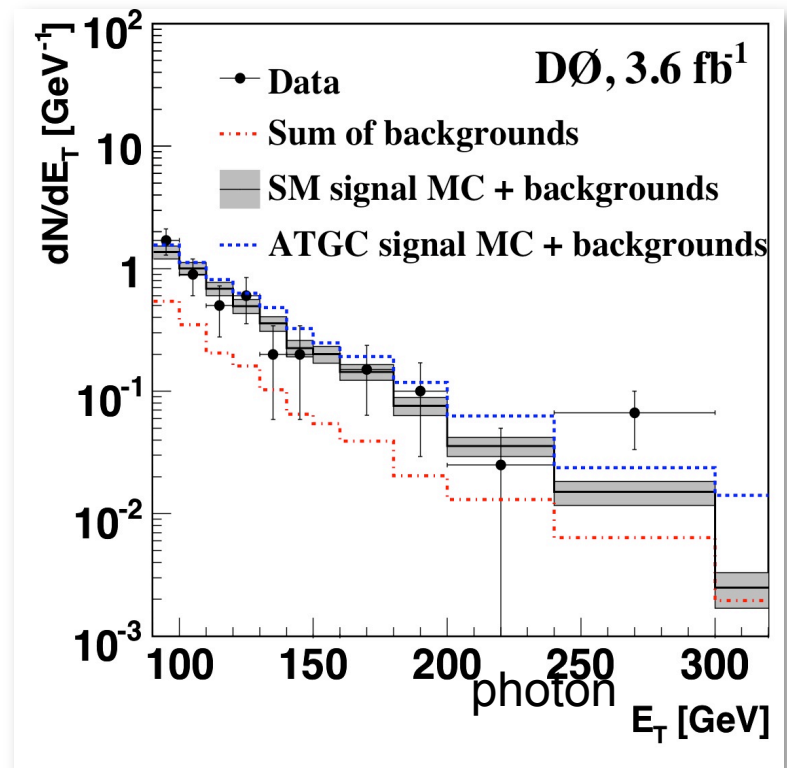
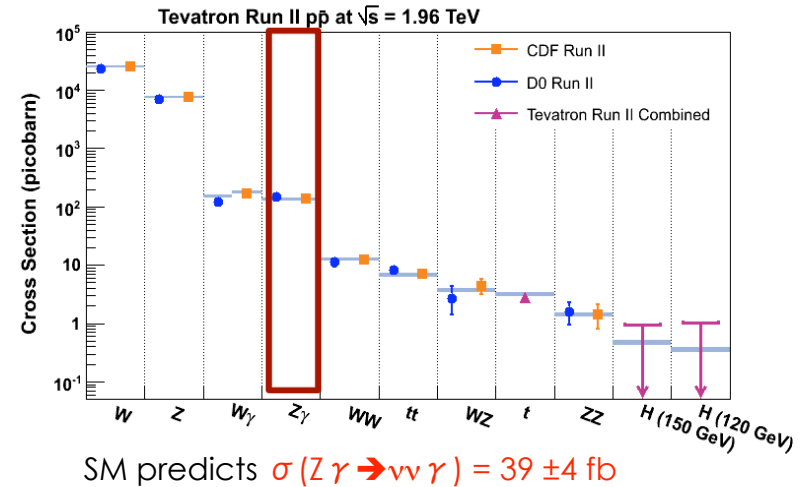
D0 (3.6 fb^{-1}):

$$\sigma(Z\gamma \rightarrow \nu\nu\gamma) = 32 \pm 9(\text{stat+syst}) \pm 2(\text{lumi}) \text{ fb}$$

- First observation, 5.1σ significance
- A new channel to test **non-abelian electroweak structure** in detail



- Limits on anomalous triple gauge couplings (aTGC) combining with $Z\gamma \rightarrow \ell\ell\gamma$ to produce some of the **most stringent limits** on **neutral aTGC**



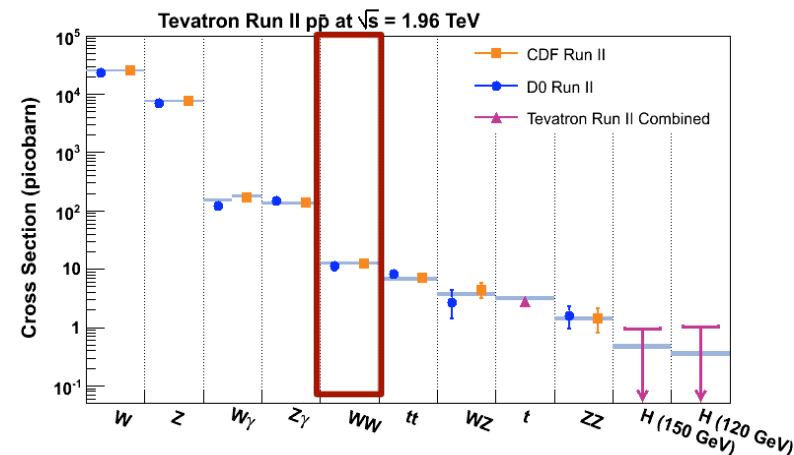
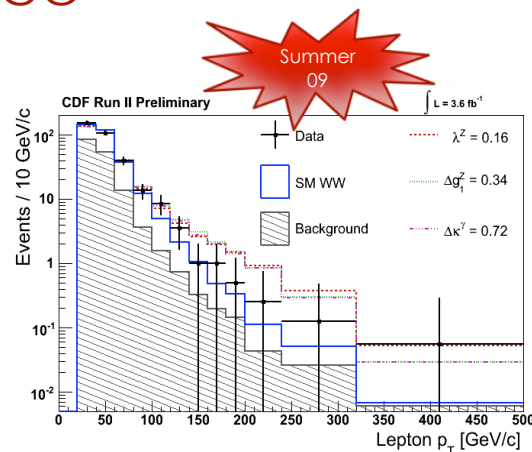
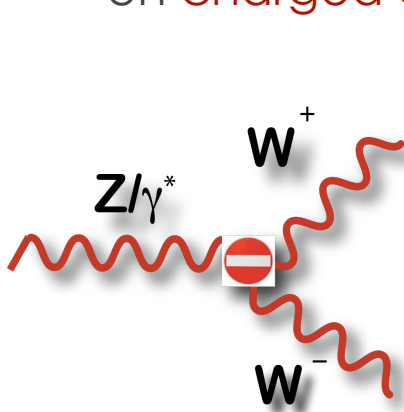
WW

- Measured in $WW \rightarrow l\nu l\nu$, offers a **clean** and relatively **high statistics** final state
- A good understanding and modeling of WW production is essential to any $H \rightarrow WW$ search

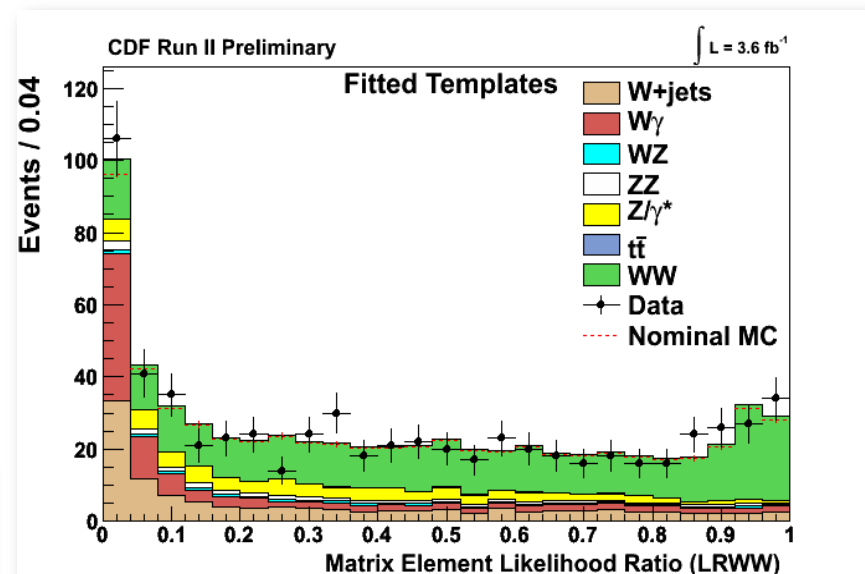
CDF (3.6 fb⁻¹):

$$\sigma(WW) = 12.1 \pm 0.9(\text{stat}) \pm 1.6_{1.4}(\text{syst}) \text{ pb}$$

- D0 (1 fb⁻¹) measures $\sigma(WW) = 11.5 \pm 2.1(\text{stat}) \pm 0.7(\text{syst}) \text{ pb}$
- D0 and CDF use **lepton p_T** to set limits on **charged aTGC**



SM predicts $\sigma(p\bar{p} \rightarrow WW) = 12.4 \pm 0.8 \text{ pb}$



Use a matrix element likelihood method to assign probability to signal/background based on event kinematics

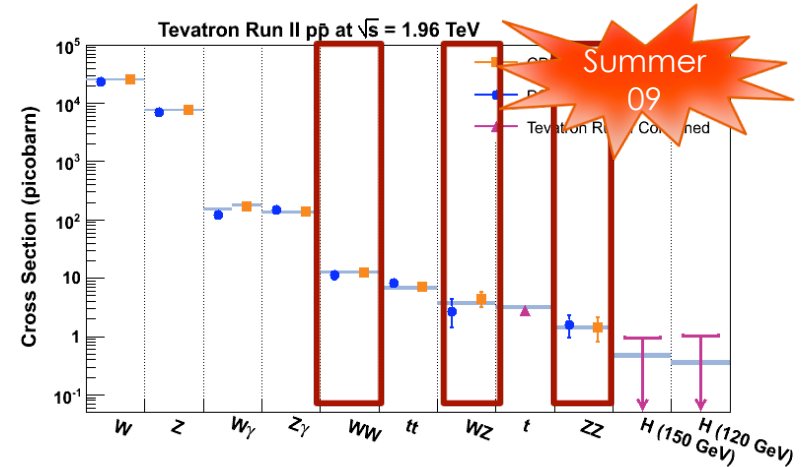
WW/WZ/ZZ

- Search for VV (V=W,Z) where one boson decays **hadronically**
 - Signal / Background ~ 3%
 - EWK background: V+jets + top (~85%)
 - QCD background: instrumental (~15%)
 - No charged lepton requirement
 - Includes $\nu\nu qq'$ as well as $l\nu qq'$ final states

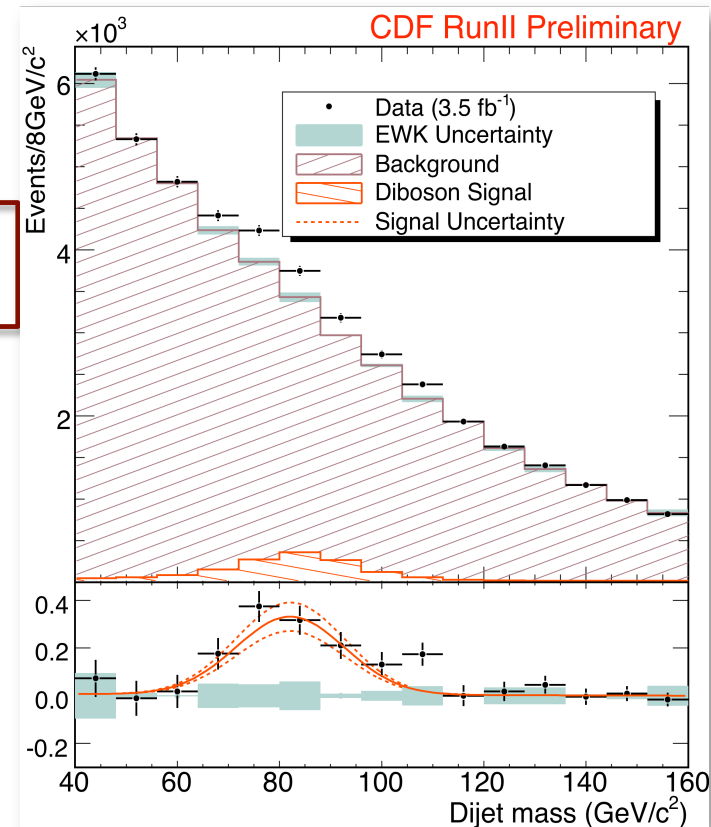
CDF (3.5 fb⁻¹):

$\sigma(WW/WZ/ZZ) = 18.0 \pm 2.8(\text{stat}) \pm 2.6(\text{syst}) \text{ pb}$

- First observation of diboson with hadronic decays, 5.3 σ significance



SM predicts $\sigma(pp \rightarrow WW+WZ+ZZ) = 16.8 \pm 0.5 \text{ pb}$



Fit invariant dijet mass in the event

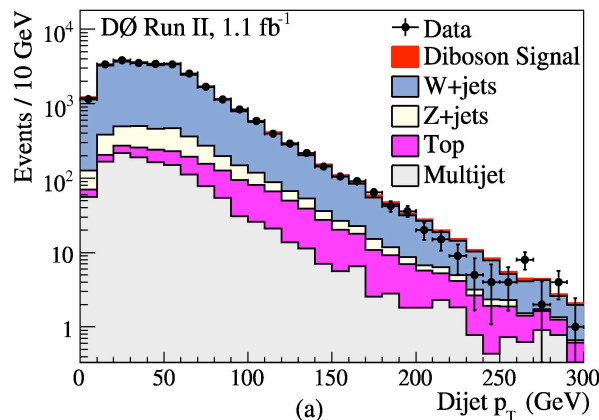
WW/WZ

- $WW/WZ \rightarrow l \nu jj$ where we require a lepton is the main background in WH and ZH searches
- Different composition than previous analysis: overlap is $\sim 20\%$
- WW and WZ are experimentally hard to distinguish in hadronic channels

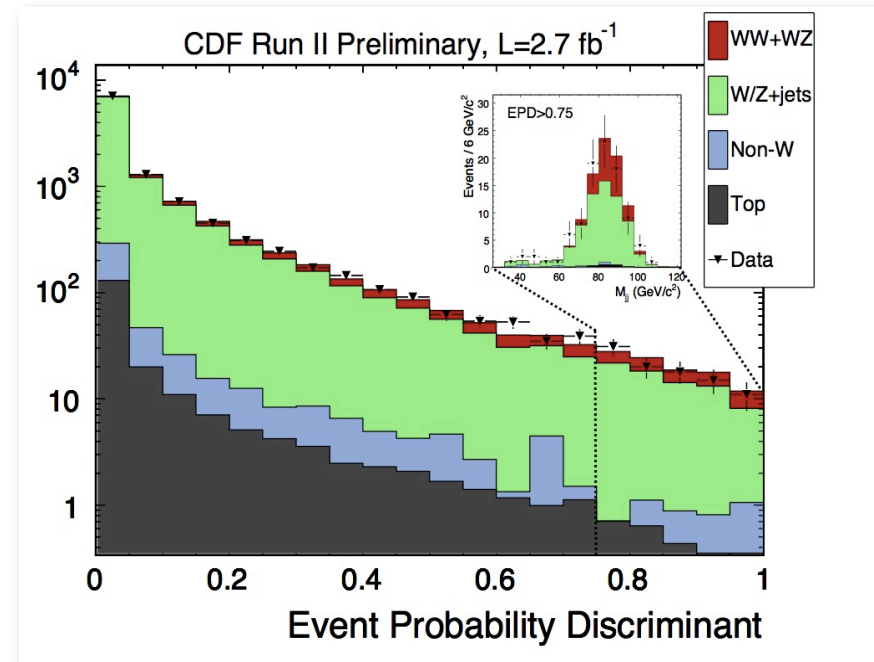
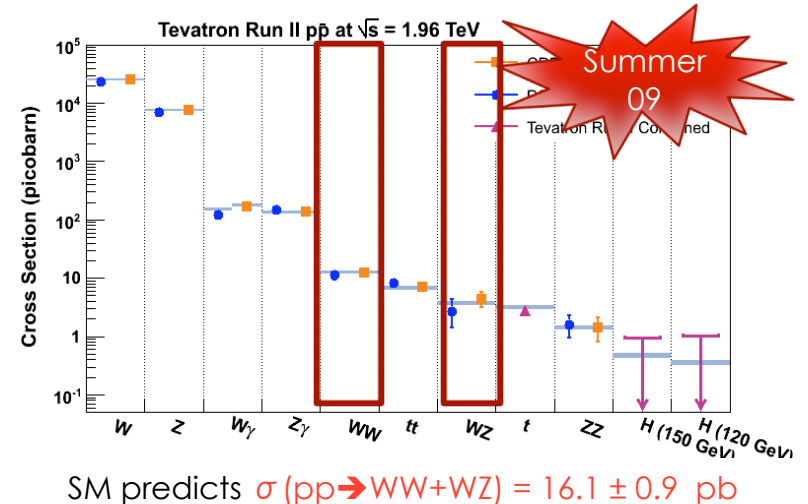
CDF (2.7 fb⁻¹):

$$\sigma(WW/WZ) = 17.7 \pm 3.9(\text{stat}) \pm 1.6_{1.4}(\text{syst}) \text{ pb}$$

- First observation, 5.4σ significance
- Evidence presented by D0 (1 fb⁻¹)
 $\sigma(WW+WZ) = 20.2 \pm 4.5 \text{ pb}$



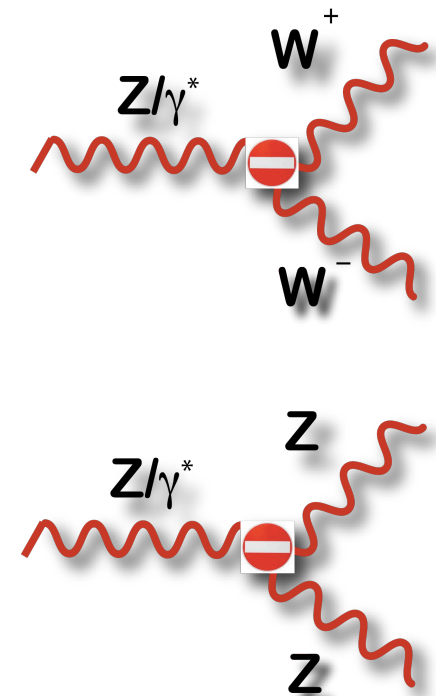
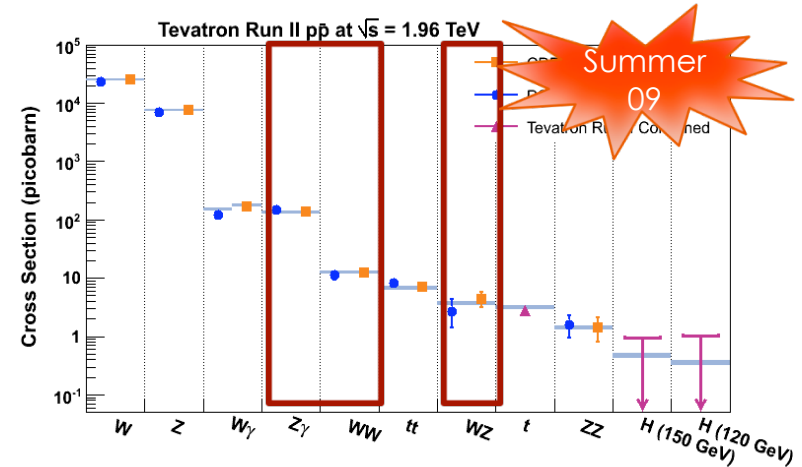
- First αTGC limits in this channel



Discriminant based on probabilities built using matrix elements for signal and backgrounds

TGC Summary

- **Charged TGC:** D0 combines limits using up to 1 fb⁻¹ of data
 - WW/WZ → l ν jj, WW → l ν l ν, WZ → l ν ll, WY → l ν Y
 - $\kappa_\gamma = 1.07^{+0.16}_{-0.20}$, $\lambda = 0.00^{+0.05}_{-0.04}$ and $g_1^Z = 1.05^{+0.06}_{-0.06}$
 - Results close to LEP2 individual results in λ ; 2x g_1^Z ; 2-3x $\Delta \kappa_\gamma$
 - A combination with CDF results and 5 fb⁻¹ of data will reduce the statistical uncertainty by a factor of 3, comparable or better results to LEP combined
 - W boson magnetic dipole moment $\mu_W = 2.02^{+0.08}_{-0.09} (e/2M_W)$
 - Electric quadrupole moment $q_W = -1.00 \pm 0.09 (e/M_W^2)$
- **Neutral TGC:** D0's best limits in
 - $|h_{30}^r| < 0.033$, $|h_{40}^r| < 0.0017$ and $|h_{30}^Z| < 0.033$, $|h_{40}^Z| < 0.0017$



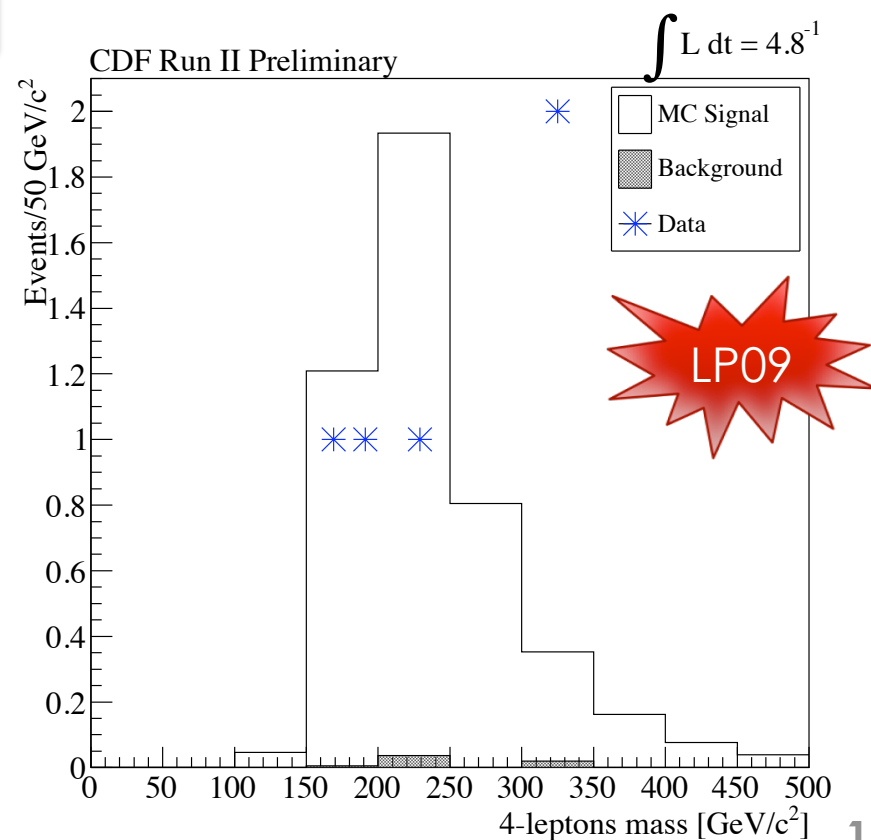
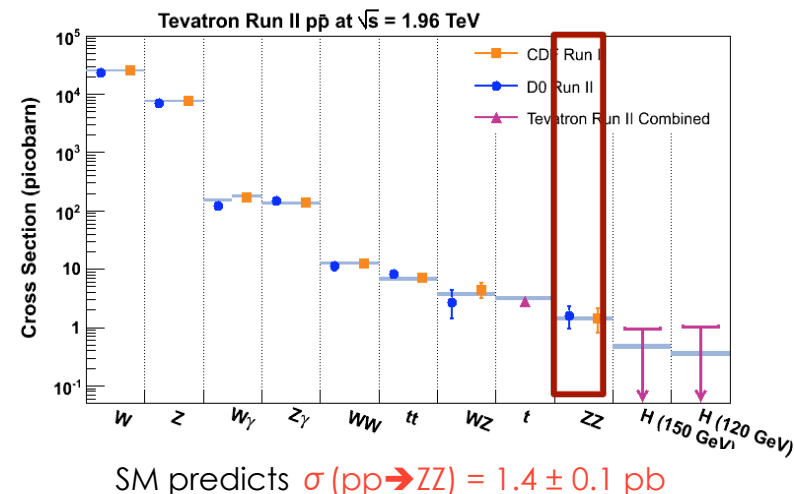
ZZ

- Smallest cross section of SM diboson states
- $ZZ \rightarrow \ell\ell\ell\ell$ striking signature !
 - First observation by D0 , 5.3 σ significance

CDF (4.8 fb⁻¹):

$$\sigma(ZZ) = 1.56^{+0.80}_{-0.63} \text{ (stat.)} \pm 0.25 \text{ (syst.) pb}$$

- 5.7 sigma significance
- $ZZ \rightarrow \ell\ell j j$ or $ZZ \rightarrow \nu\nu j j$ mode not observed yet at the Tevatron
- Important benchmark for Higgs searches (ZH)



W, Z, and Dibosons at the LHC

■ W, Z

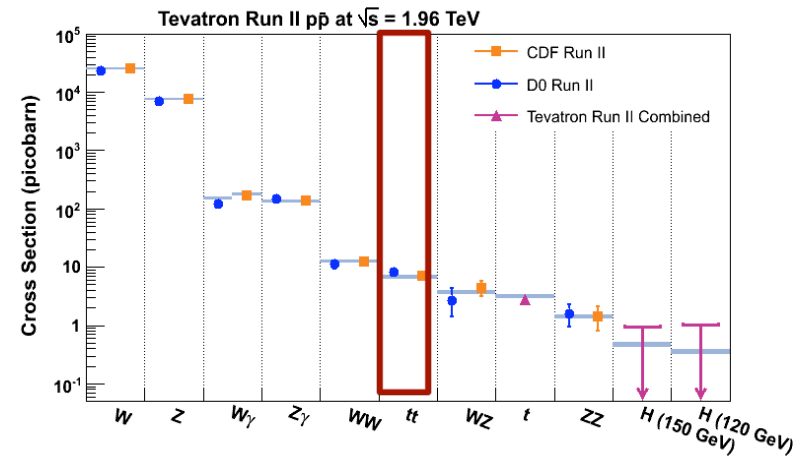
- LHC experiments expected to have much higher cross section
 - ~2 million $Z \rightarrow \ell\ell$ in the first fb^{-1}
 - Tevatron now has reconstructed up to 1.6 million $Z \rightarrow \ell\ell$
 - With a 100 fb^{-1} expect $\sin^2\theta_W$ competitive result to current world average

■ Dibosons

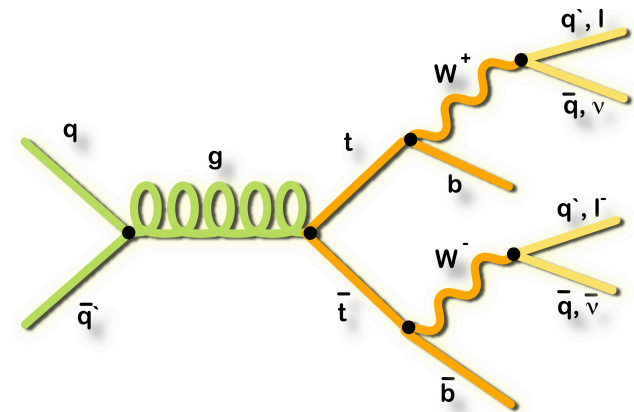
- LHC experiments have 10 times the Tevatron cross section
- In 10 fb^{-1} of data \rightarrow factor of 100 in statistics and 10 in sensitivity relative to current TGC Tevatron
- 200 fully reconstructed ZZ events in first 10 fb^{-1} !!

Top Quark Pairs

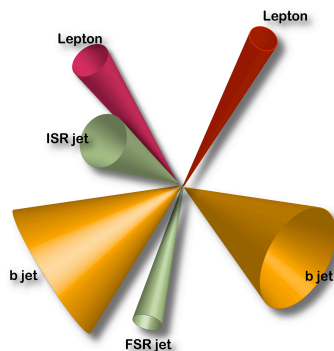
- QCD pair production is the **dominant source of top quarks** for study
- Cross section measurement tests perturbative **QCD at a higher energy scale**
 - Surprisingly large mass, $m_t \sim 175$ GeV!
- Produced **via QCD through qq or gg** and decays via EWK, $BR(t \rightarrow Wb) \sim 100\%$
- Striking signature defined by the decay of the W boson:



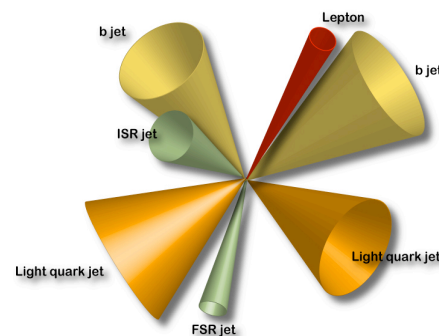
SM predicts ($m_t = 172.5$ GeV): σ (NLO) = $7.4^{+0.5}_{-0.7}$ pb



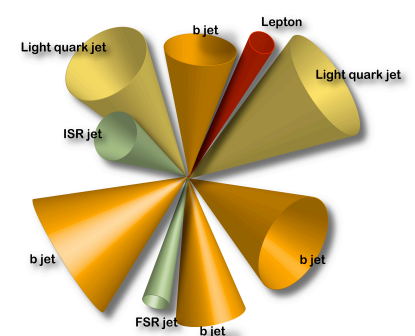
Dilepton



Lepton+Jets



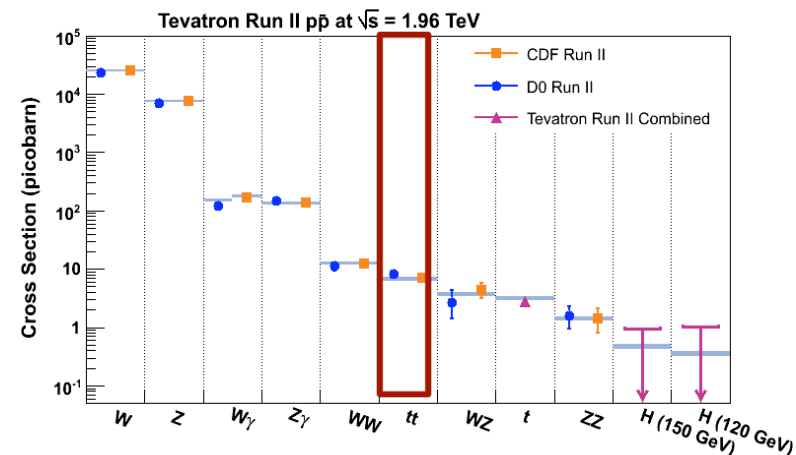
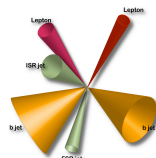
All-Hadronic



Top Quark Pairs

- **Dilepton (lepton = e or μ) (7%):**

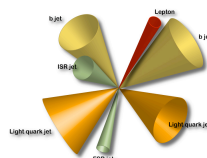
- Small rate, small backgrounds
- Main background: Drell-Yan



SM predicts ($m_t=172.5$ GeV): σ (NLO) = $7.4^{+0.5}_{-0.7}$ pb

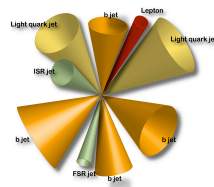
- **Taus (hadronic decay +lepton/jets) (15%):**

- Small rate, large backgrounds
- Main backgrounds: multijet and W+jets



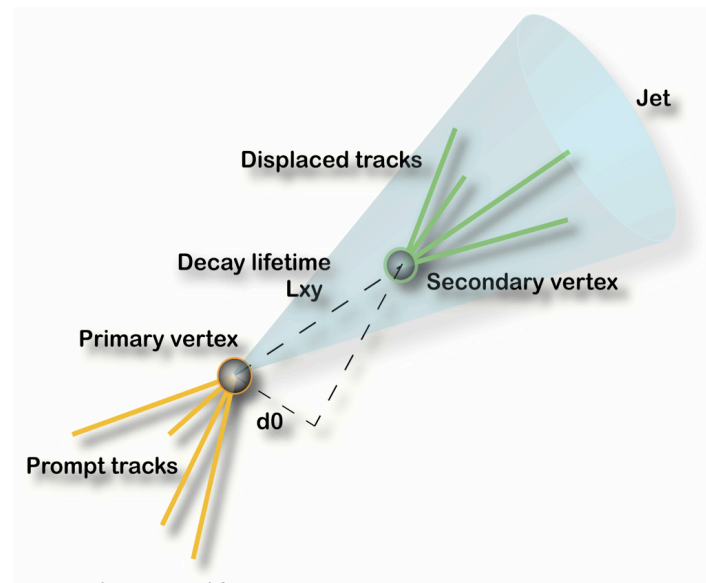
- **Lepton+Jets (lepton = e or μ) (34%):**

- Good rate and manageable backgrounds
- Main background: W+jets



- **All-hadronic (44%):**

- Large rate, large background
- Main background: multijet



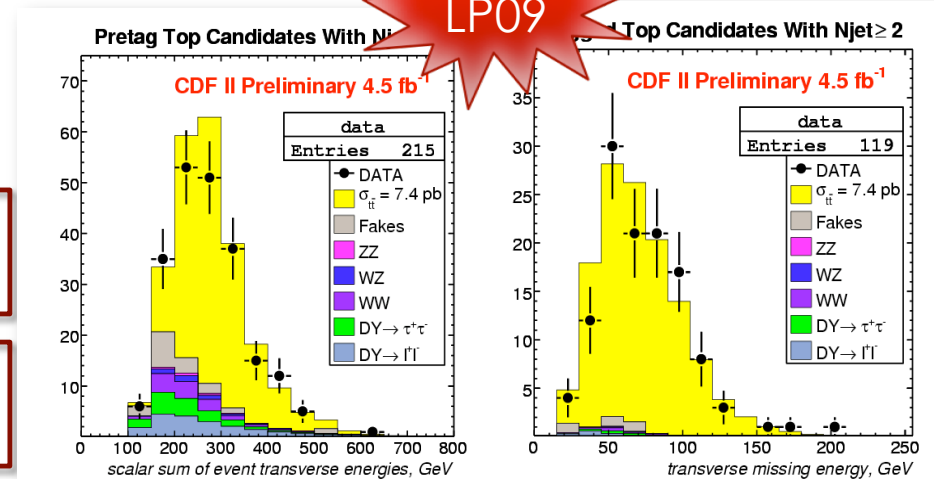
Can identify b-quarks through secondary vertex to reduce backgrounds (non-W without bottom/charm, W+light flavor jets)

Top Quark Pairs: Dilepton and All-Hadronic

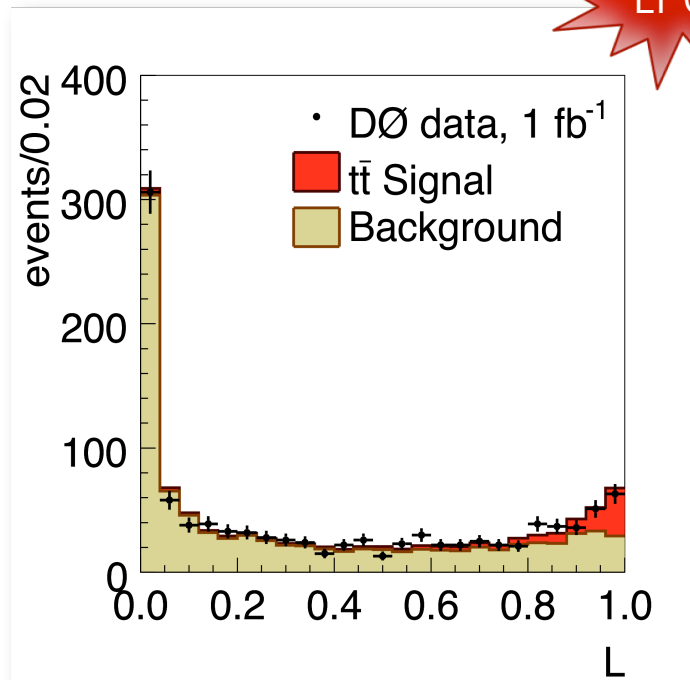
- Measure cross section in a tagged and pre-tagged dilepton sample
=> good test of signal model

CDF (4.5 fb⁻¹, m_t = 172.5 GeV), b-tagged:
 $\sigma_{\#}(\text{dil}) = 7.3 \pm 0.7(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$

CDF (4.5 fb⁻¹, m_t = 172.5 GeV), pre-tagged, :
 $\sigma_{\#}(\text{dil}) = 6.6 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$



- Consistent results



- Measure cross section in a background dominated sample

- Background is hard to model
 - Poorly known cross sections
 - Data driven background model

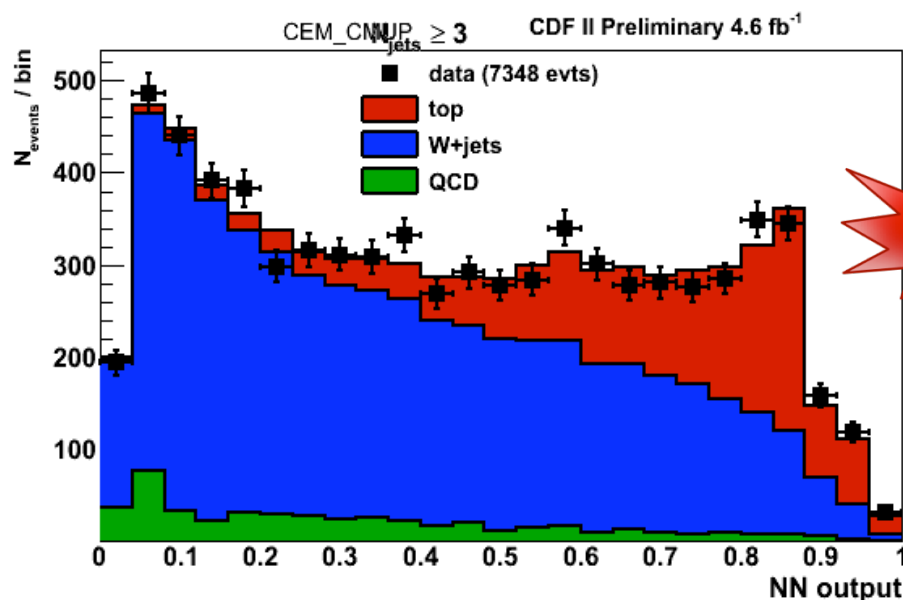
- Train NN on signal and background to purify the sample

CDF (2.9 fb⁻¹, m_t = 172.5 GeV):
 $\sigma_{\#}(\text{all-had}) = 7.2 \pm 0.5(\text{stat}) \pm 1.5(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$
D0 (1 fb⁻¹, m_t = 175 GeV):
 $\sigma_{\#}(\text{all-had}) = 6.9 \pm 1.3(\text{stat}) \pm 1.4(\text{sys}) \pm 0.4(\text{lumi}) \text{ pb}$

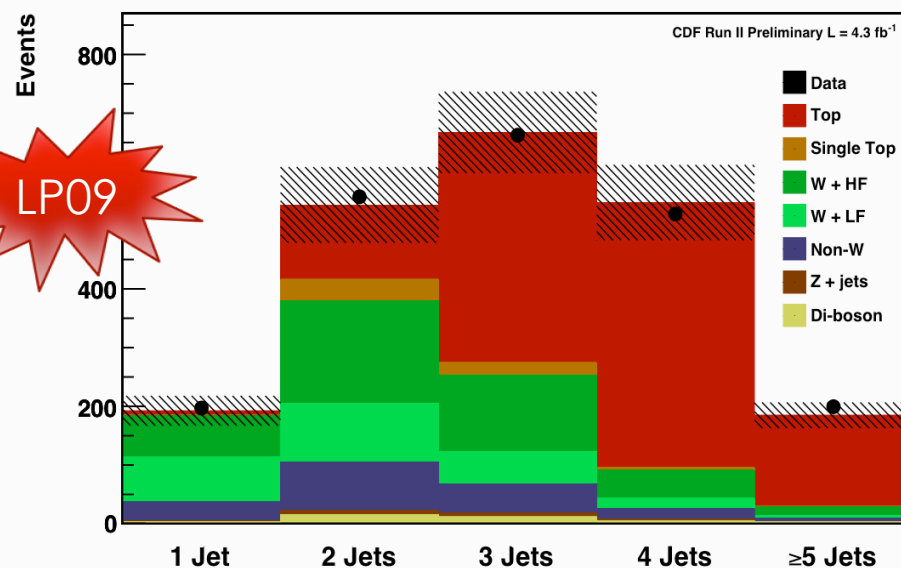
Top Quark Pairs: Lepton+Jets

- Two different methods with very different S:B
 - pre-tagged:** topological separation of signal and background via neural net
 - b-tagged:** counting experiment
- Luminosity is the largest uncertainty in both measurements
 - Reduce by normalizing to the measured Z cross section
 - Measure R and multiply by Z cross section from theory

$$\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theory}$$



LP09



CDF (4.6 fb⁻¹, $m_t = 172.5$ GeV), pre-tagged :
 $\sigma_{\#}(l+j) = 7.6 \pm 0.4(\text{stat}) \pm 0.3(\text{syst}) \pm 0.1(\text{lumi}) \text{ pb}$

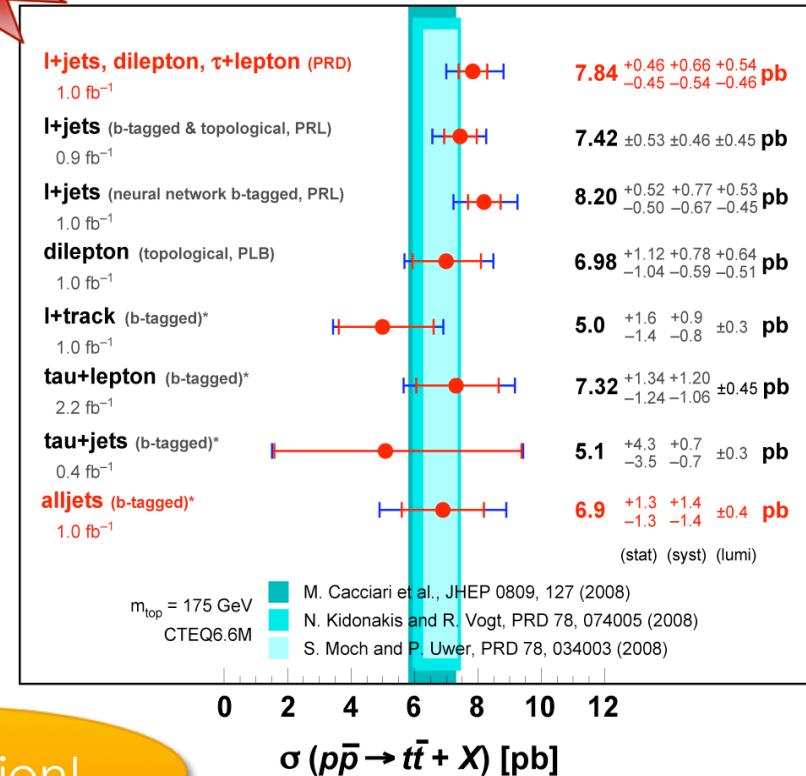
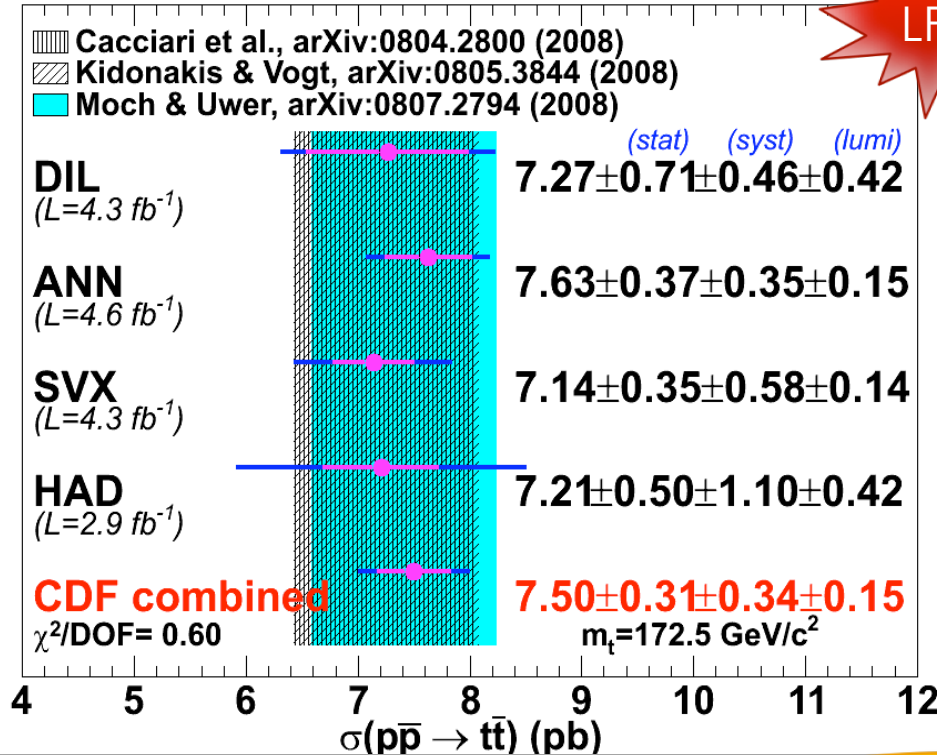
CDF (4.3 fb⁻¹, $m_t = 172.5$ GeV), b-tagged:
 $\sigma_{\#}(l+j) = 7.1 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{lumi}) \text{ pb}$

Top Quark Pairs: Combination

LP09

DØ Run II * = preliminary

August 2009

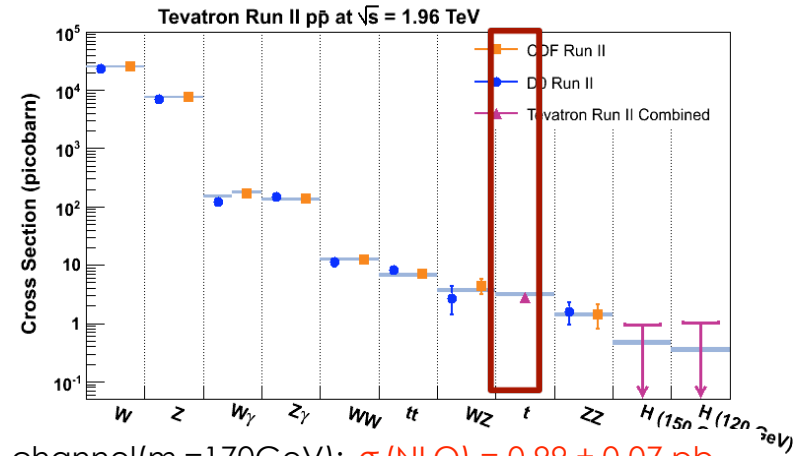


6% precision!

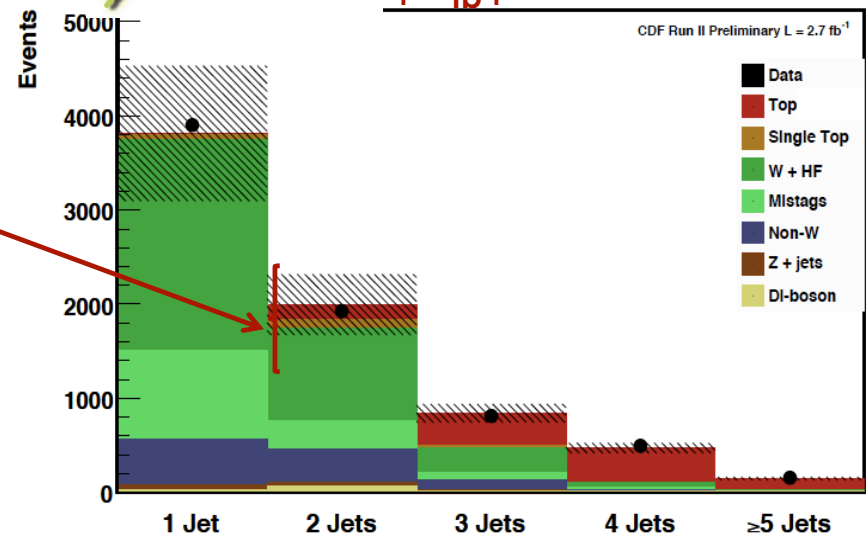
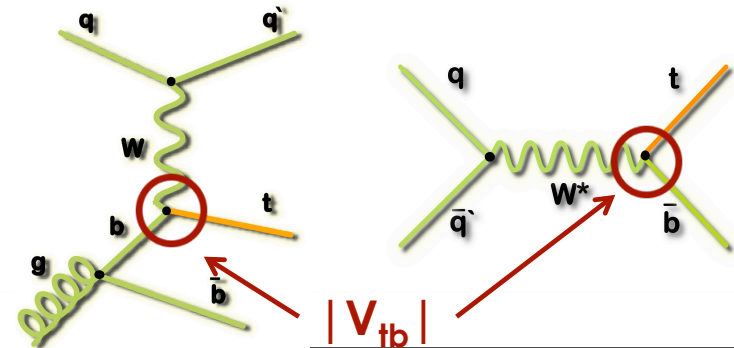
- Most CDF measurements with more than 4 fb^{-1} !
- Measurements in all channels
- All channels are consistent with each other and with theory
- Different methods to measure $\sigma_{t\bar{t}}$ produce consistent results
- Tevatron combination underway

Single Top Quark

- Electroweak production of single top quark
- Predicted in ~1985
 - t-channel: Willenbrock and Dicus, PRD 34, 155 (1986)
 - s-channel: Cortese and Petronzio, PLB 253, 494 (1991)
- Observed in 2009: 14 years after the top quark discovery!
- Not an easy measurement!
 - Small cross section
 - Large backgrounds with large uncertainties
- Allows measurement of CKM matrix element $|V_{tb}|$



s-channel($m_t=170\text{GeV}$): $\sigma(\text{NLO}) = 0.99 \pm 0.07$ pb
 t-channel($m_t=170\text{GeV}$): $\sigma(\text{NLO}) = 2.15 \pm 0.24$ pb



Single Top Quark: Tevatron Combination

- In March 2009 the Tevatron experiments reported observation of with about **5 σ** significance (to be published in PRL this week)
- CDF and D0 combined their results using a Bayesian approach:

Tevatron (3.2 fb⁻¹):

$$\sigma_t = 2.76^{+0.58}_{-0.47} \text{ (stat+syst) pb}$$

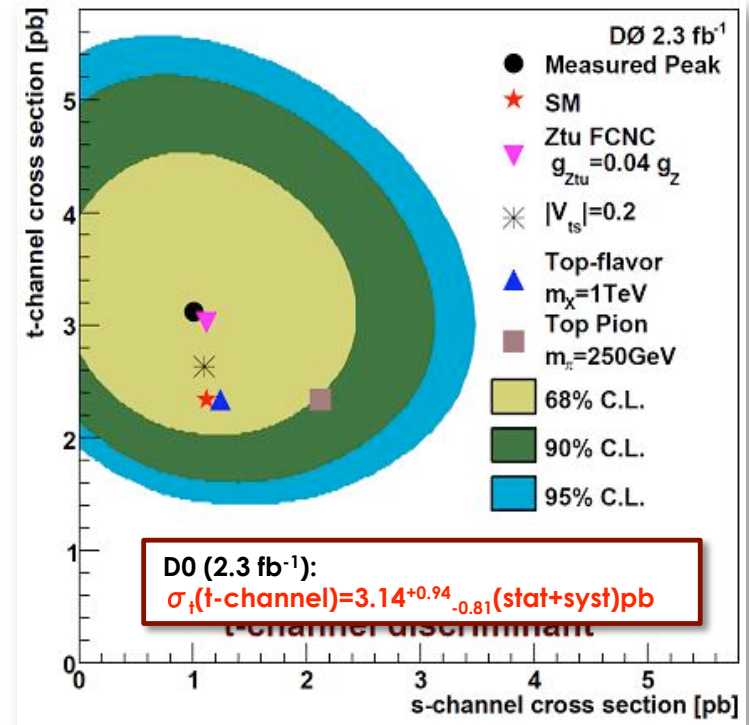
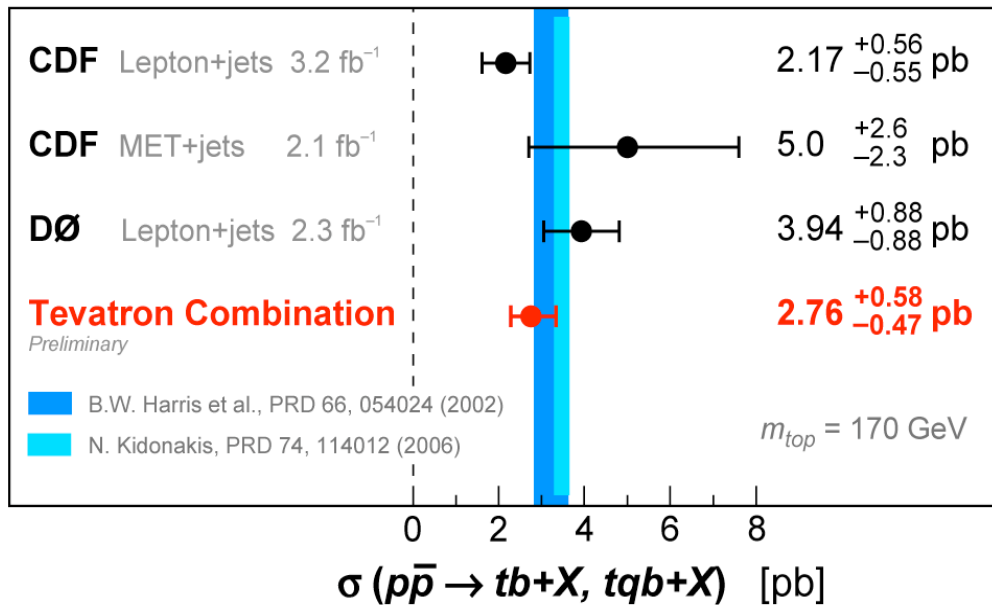
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Tevatron (3.2 fb⁻¹), PRD66 054024, 2002:

$$|V_{tb}| = 0.91 \pm 0.08 \text{ (stat+syst)}$$

Single Top Quark Cross Section

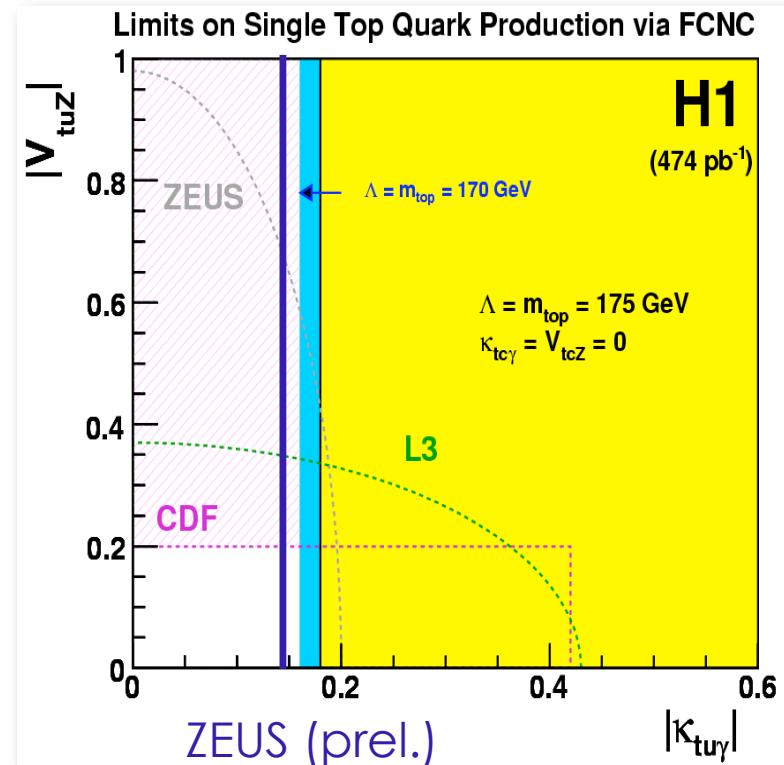
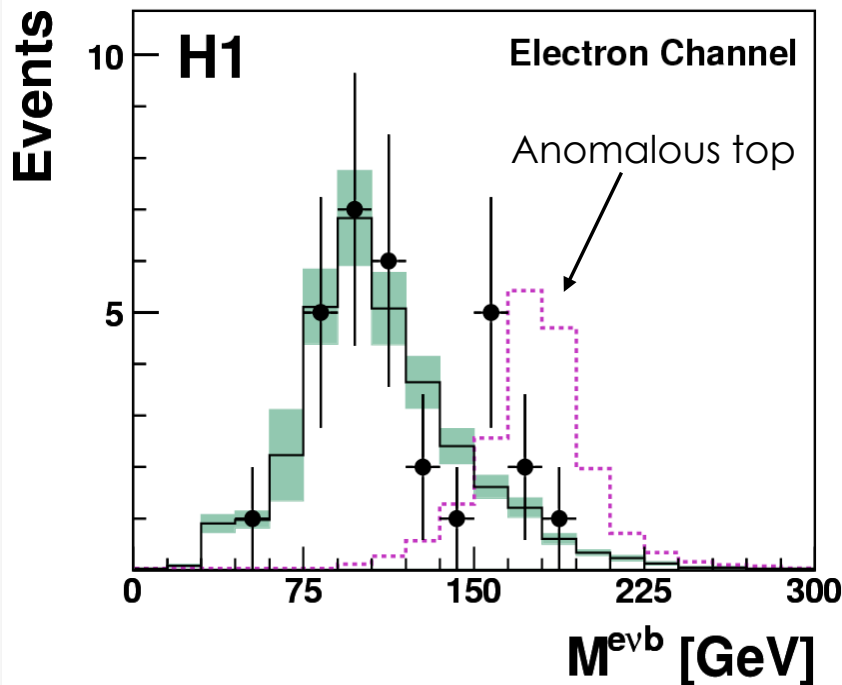
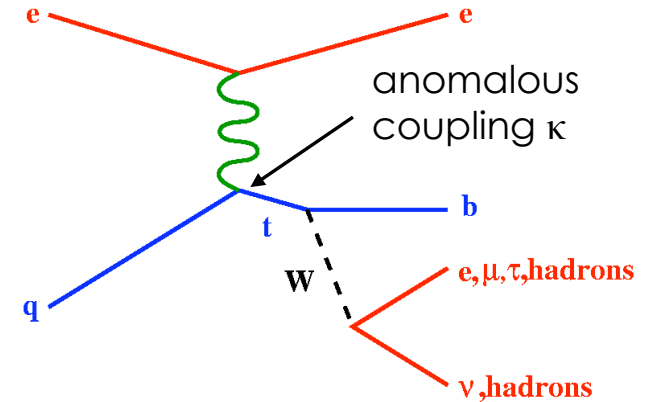
August 2009



13% improvement

Single Top Quark at Hera

- Search for single top in the e, u and hadronic W decay
- Standard model single top is strongly suppressed
- Upper limit on single top production via FCNC process $\sigma(ep \rightarrow etX)$ and limits on the anomalous couplings κ



Top Pairs and Single Top at the LHC

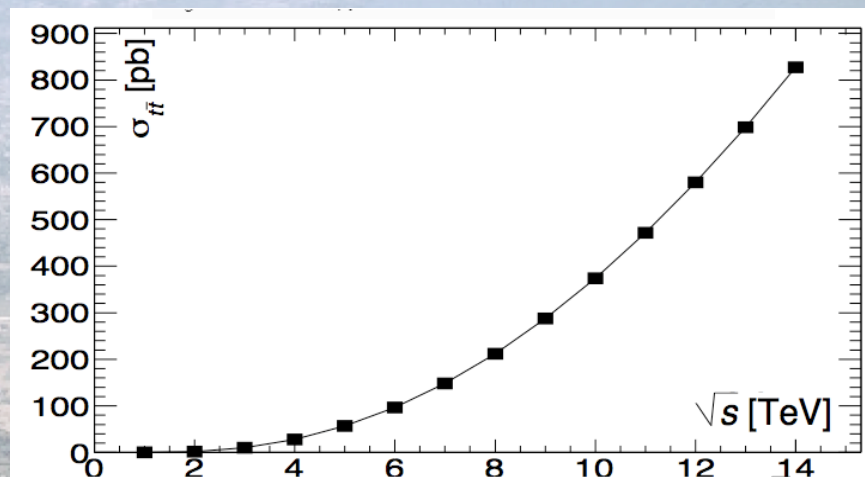
- Top quark pairs will be produced mainly by gg fusion in contrast with the Tevatron

- With 20pb^{-1} and 10 TeV in muon+jets channel $6\%(\text{stat})\pm 30\%(\text{syst})\pm 10\%(\text{lumi})$ (CMS)

- Long run expect to reach comparable precision or better than the Tevatron

- Important calibration tools for b-tagging algorithms and jet energy scale corrections and systematic uncertainties

- Given the richness of the top signatures *“when top measured, experiment is ready for discovery phase”* from K. Jon-And’s talk



- Single top quarks production channels will include associated production (Wt) and not very sensitive to s-channel

- Precision measurements of properties of top in electroweak produced top quarks will be possible

Precision Measurements

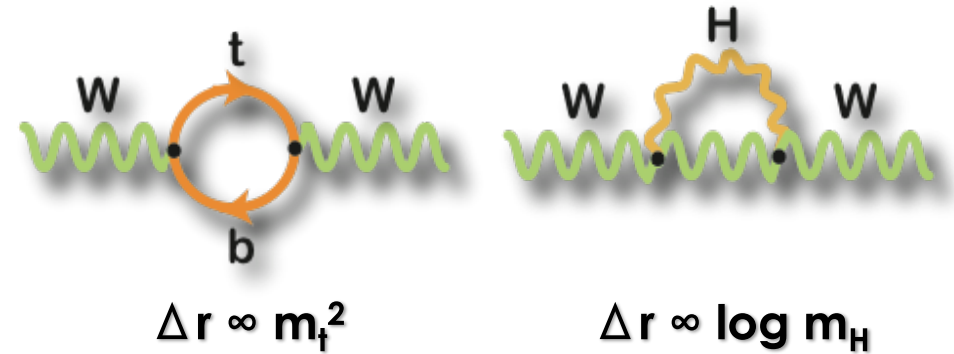
W boson mass

Top quark mass

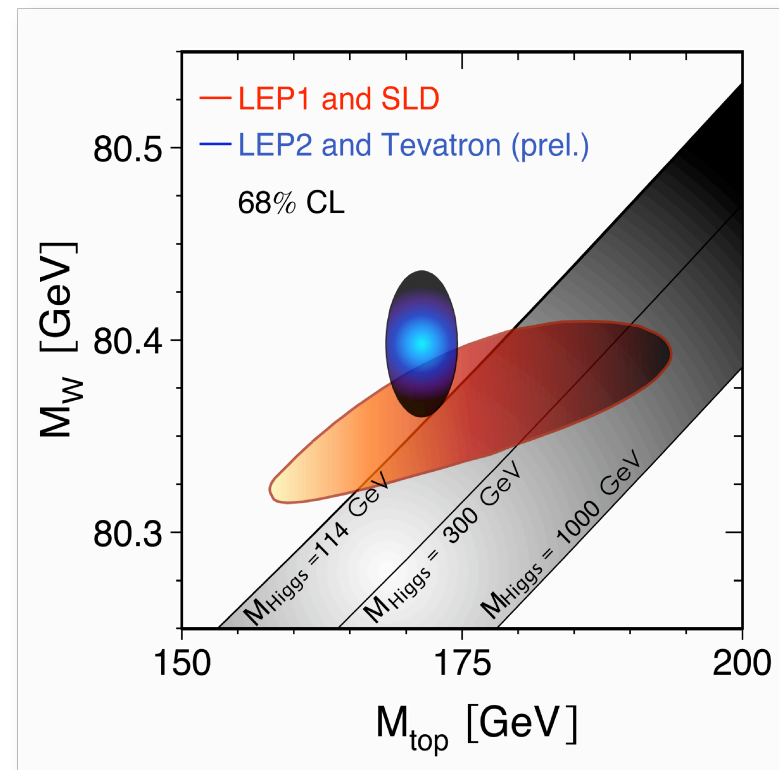
Predictions for Higgs boson mass

W Boson, Top Quark, and Higgs Boson

- Measuring the **W boson mass** and **top quark mass** precisely allows for prediction of the **mass of the Higgs boson**



- Constraint on Higgs can point to **physics beyond the standard model**
- Constrains the Higgs mass now, **precision check of the EW theory** after/if Higgs is found

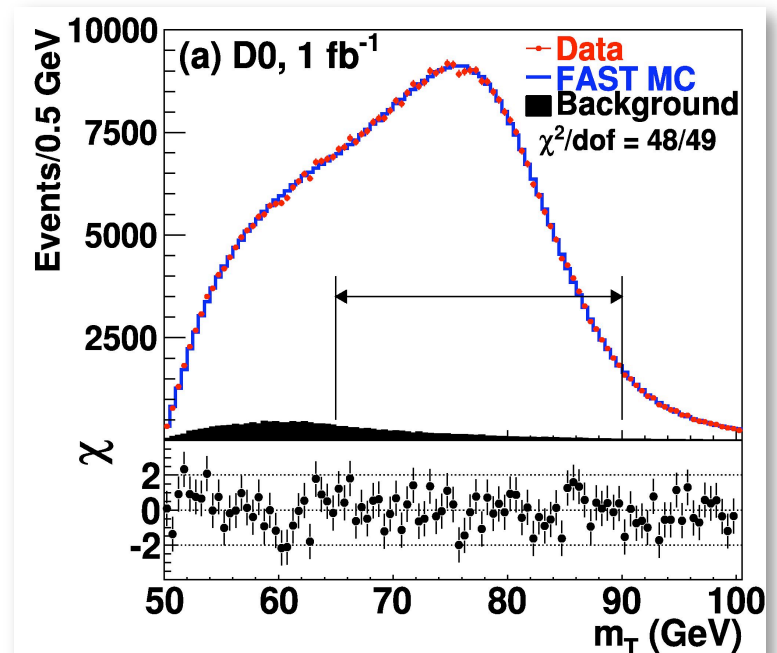
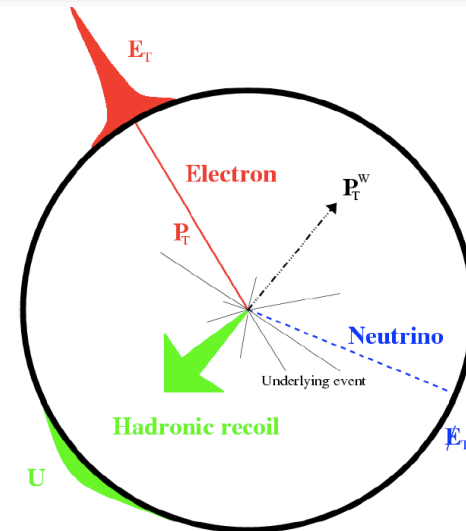


W Boson Mass: Most Precise Result

- At hadron colliders, rely on transverse variables: m_T , p_T^e , missing E_T = inferred neutrino p_T^ν
 - m_T most accurate
 - Requires precise measure of charged lepton p_T and hadronic recoil
- Use **well-measured resonances** to calibrate Z boson, J/ψ , Υ
 - Requires detailed knowledge of detectors
- Perform **fits to templates** generated from calibrated simulation by varying m_W
- Measurement in the electron channel combining 3 fits: m_T , p_T and missing E_T

D0 (1 fb⁻¹):

$m_W = 80401 \pm 21(\text{stat}) \pm 38(\text{syst}) \text{ MeV}$



W Boson Mass: Most Precise Result

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D0 (1 fb⁻¹):

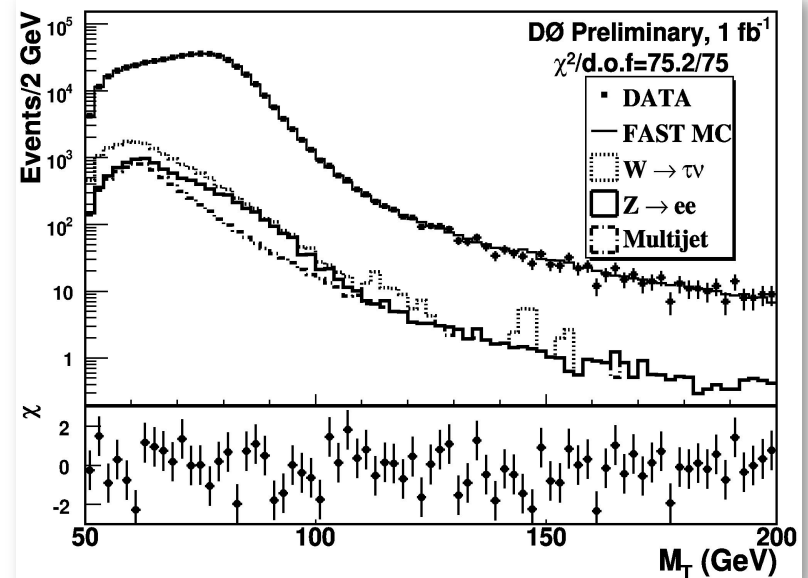
$m_W = 80401 \pm 21(\text{stat}) \pm 38(\text{syst}) \text{ MeV}$

Using similar techniques and dataset, D0 measures W top width by fitting m_T tail

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D0 (1 fb⁻¹):

$\Gamma_W = 2.028 \pm 0.072(\text{stat}) \pm 38 \text{ GeV}$



W Boson Mass: Future Precision

- Limited by the size of the Z sample. Will improve with more data
- Tevatron measurements improving the precision of parton distributions functions (ex. W charge asymmetry previously shown)

Tevatron goal is 25 MeV per experiment

D0 m_W Systematic Uncertainties (1 fb^{-1})

Systematic Source	δm_W (MeV)
Electron energy scale	34
Electron energy resolution model	2
Electron energy nonlinearity	4
W and Z electron energy loss differences	4
Recoil model	6
Electron efficiencies	5
Backgrounds	2
PDF	9
QED	7
Boson p_T	2
Total	37

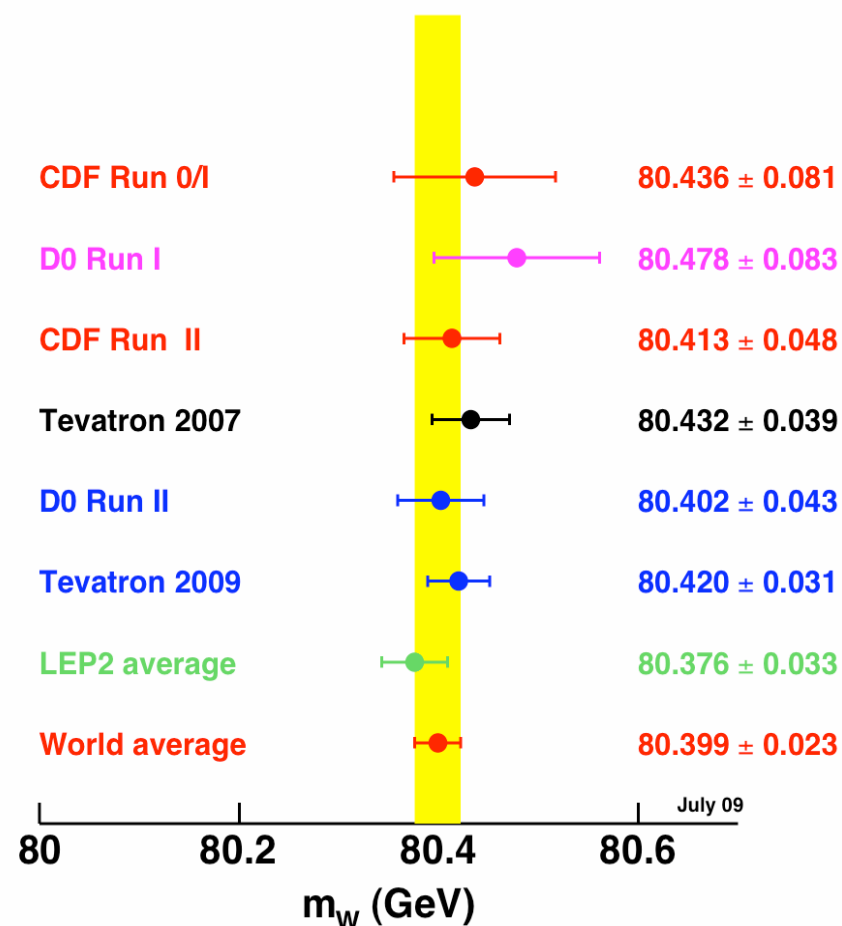
W Boson Mass: Tevatron Combination

- Combine previous results, including CDF Run II measurement using 200 pb⁻¹: $m_W = 80413 \pm 34(\text{stat}) \pm 34(\text{syst}) \text{ MeV}$

Tevatron Average:
 $m_W = 80420 \pm 31 \text{ MeV}$

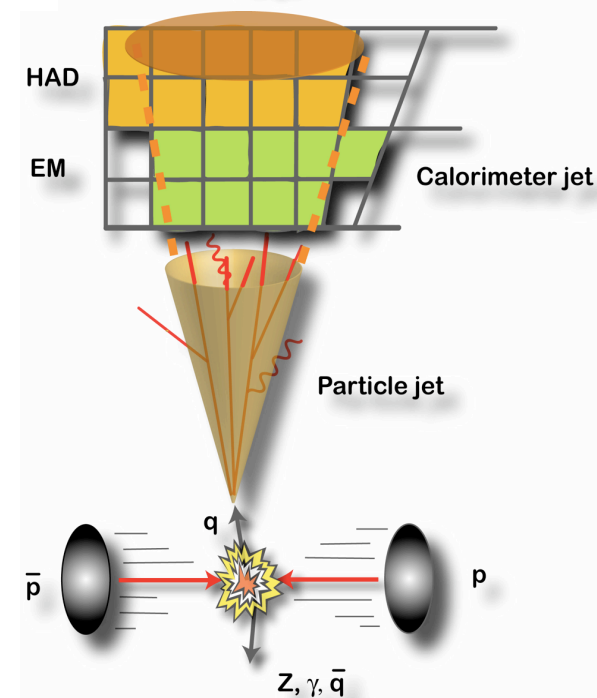
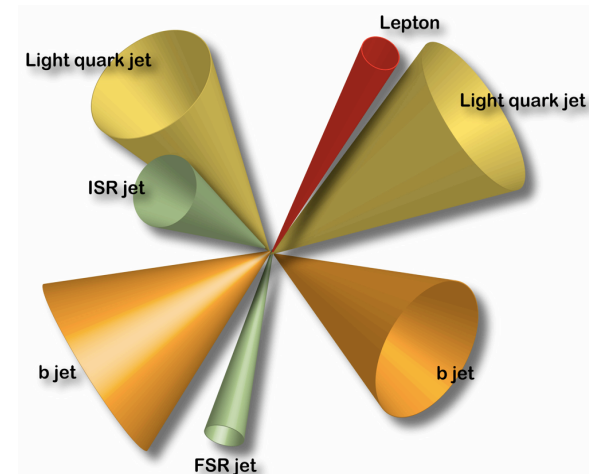
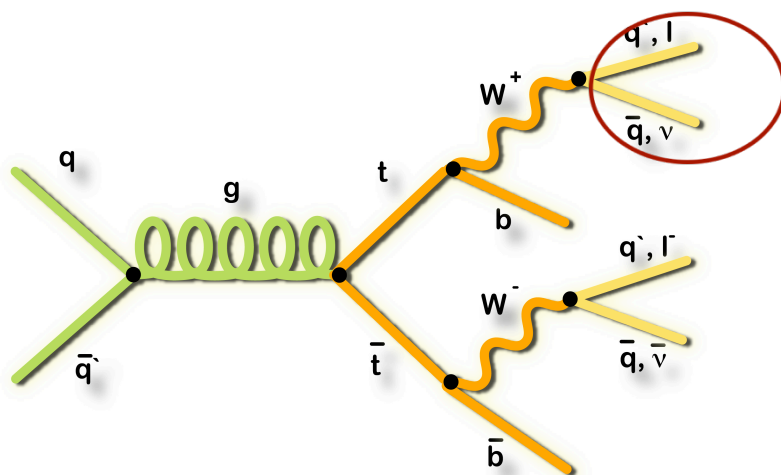
World Average:
 $m_W = 80399 \pm 23 \text{ MeV}$

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Top Quark Mass

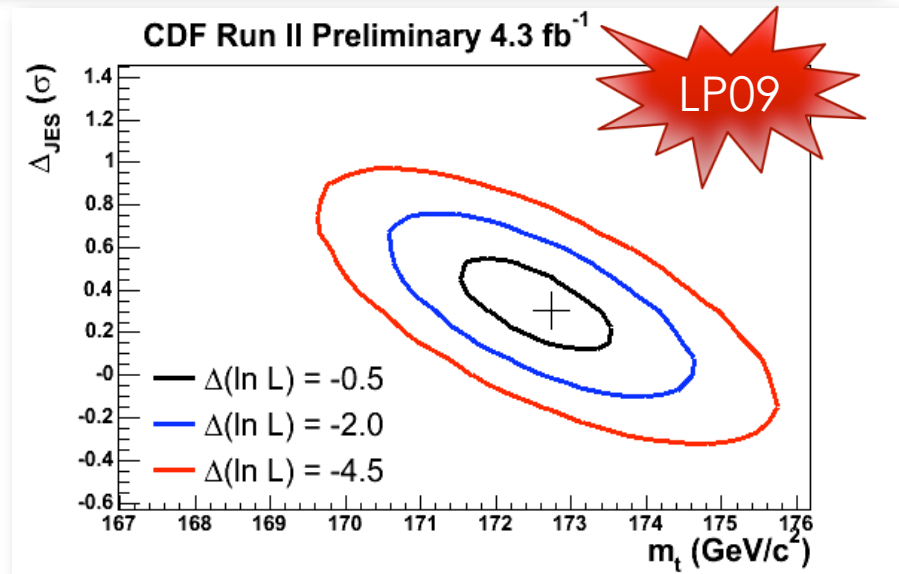
- Measurements in the 3 channels: **dilepton**, **lepton +jets**, **all-hadronic**
- Different **difficulties** than in W mass measurement
 - Can only measure jets resulting from quarks
 - Jet-parton assignment
 - QCD radiation
- Jet energy scale (JES) uncertainty dominates [$\sim 3\%$]
 - Can be reduced via *in situ* measurement from **hadronic W mass**



Top Quark Mass: Most Precise Result

■ Lepton + Jets and All-hadronic channels

- Fully **reconstructable** final state
 - Reduce jet combinatorics and background by requiring ≥ 1 b-tag
- Matrix element or reconstructed m_t technique for probabilities
 - **In situ JES calibration**
 - Form 2D likelihood as function of top mass and shift in JES error
- Complementary techniques independent of JES
 - L_{xy} , lepton p_T



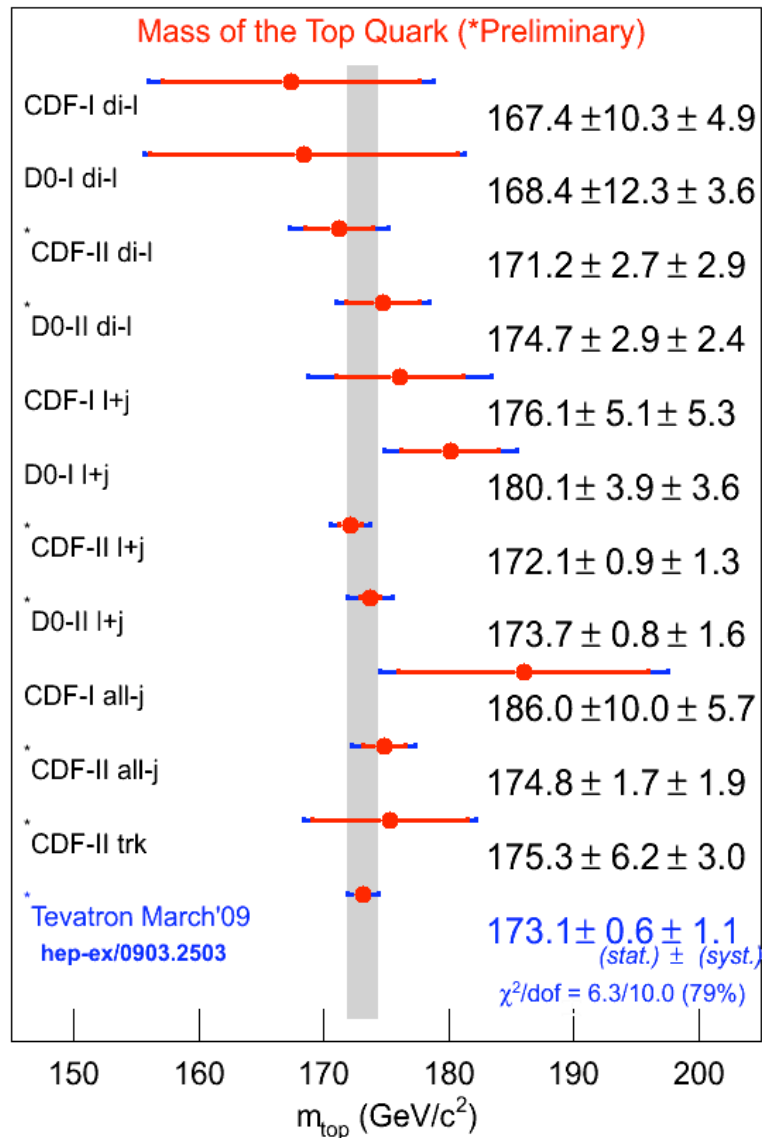
CDF (4.3 fb⁻¹):

$$m_t(l+j) = 172.6 \pm 0.9(\text{stat}) \pm 0.7(\text{JES}) \pm 1.1(\text{syst}) \text{ GeV}$$

■ Dilepton channel

- Two neutrinos result in kinematically **underconstrained** system
- Requires integration over at least one variable
- **Can't constrain JES**
- Matrix element or templates integrating over one variable

Top Quark Mass: Tevatron Combination



Tevatron (Winter 09):

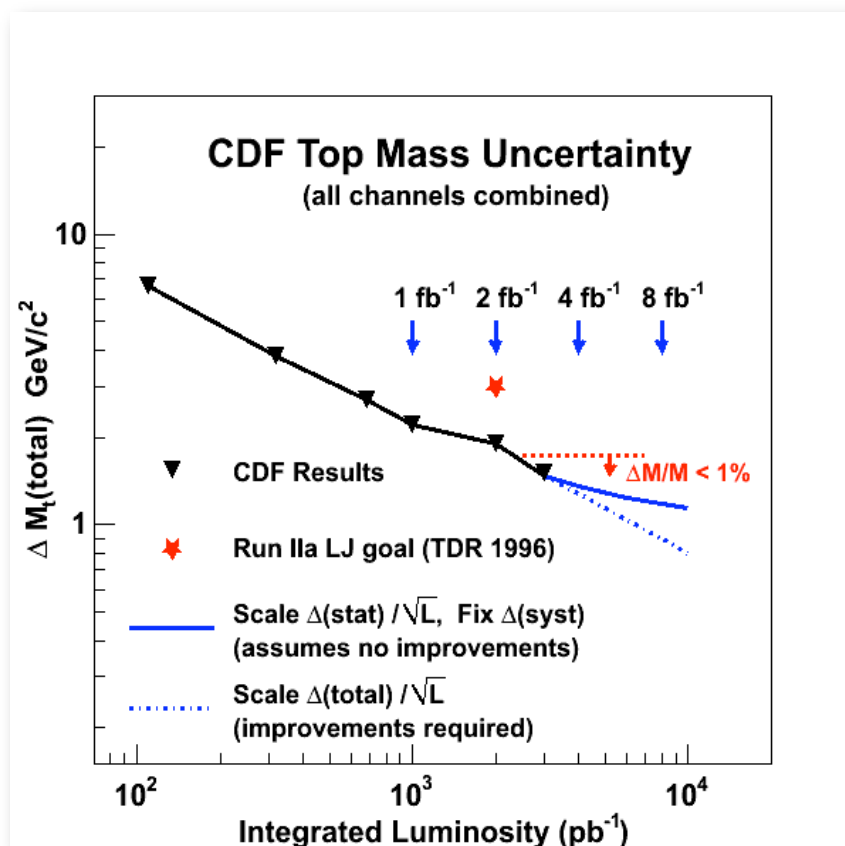
$m_t = 173.1 \pm 0.6$ (stat) ± 1.1 (syst) GeV

$m_t = 173.1 \pm 1.3$ (stat+syst) GeV

- Channels are consistent with each other
- Different methods to measure m_t produce consistent results
- Working on improving systematic uncertainties: are all effects covered, are they covered more than once ?

Top Quark Mass: Future Precision

- Using CDF as example



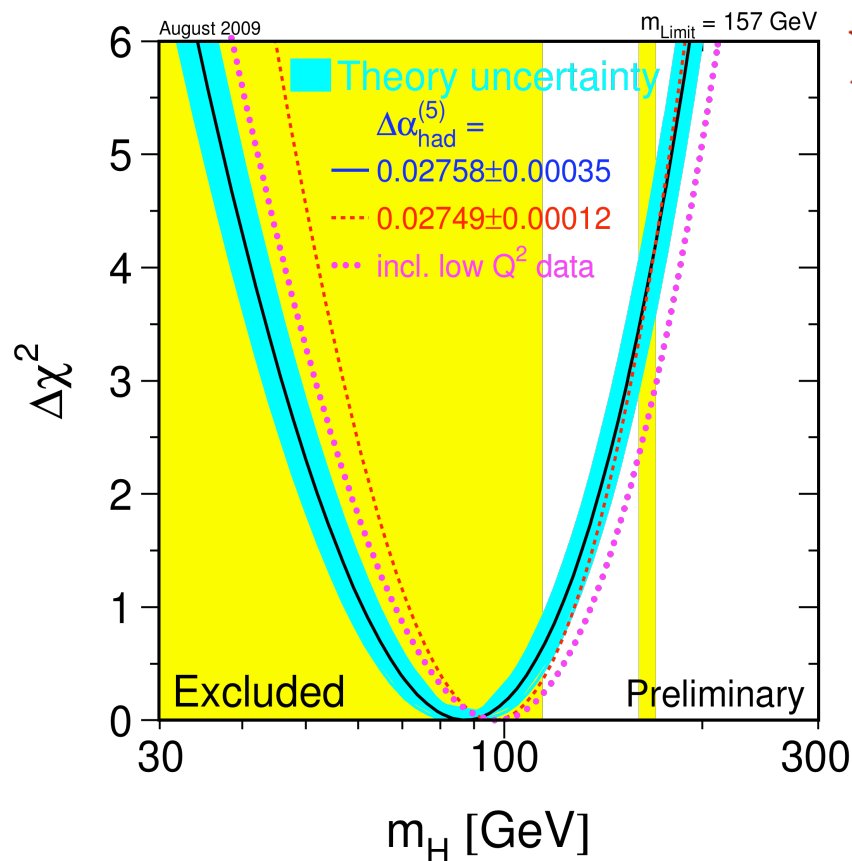
CDF m_t (l+j) Systematic Uncertainties 4.3 fb^{-1}

Systematic Source	m_{top} (GeV)
Calibration	0.1
MC generator	0.5
Radiation	0.4
Residual jet energy scale	0.5
b-jet energy scale	0.4
Lepton p_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.3
Total	1.1

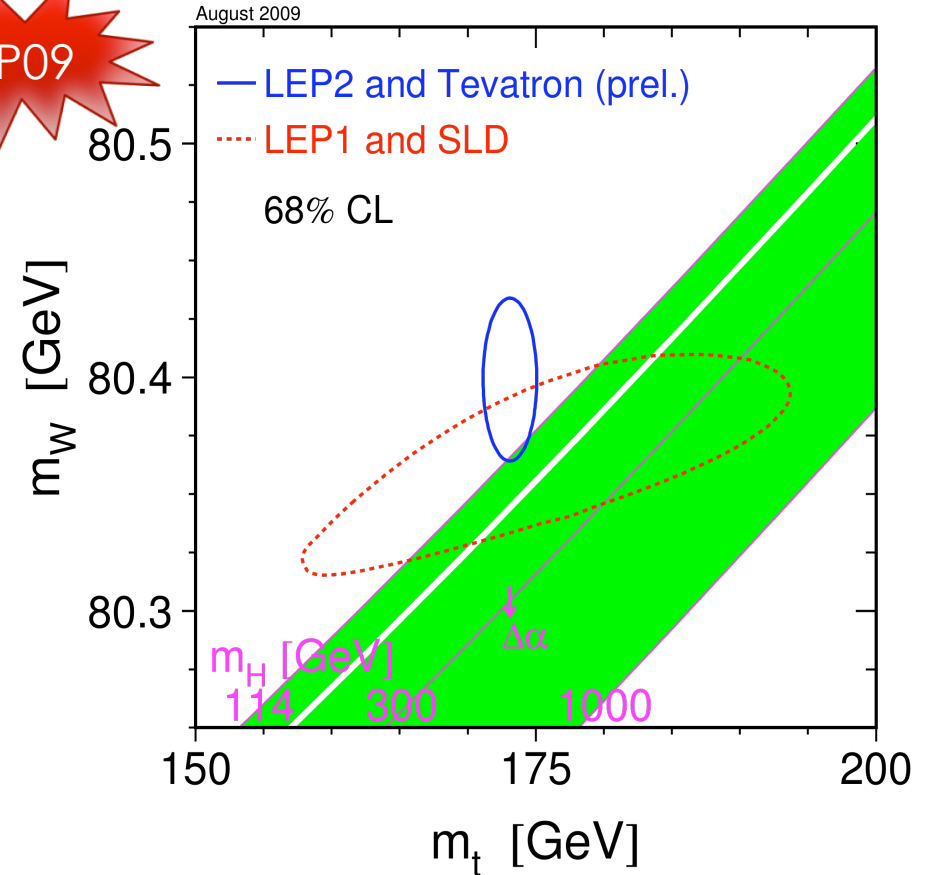
Magnitude of systematic uncertainties are comparable.
Single experiment top quark mass precision reaching 1 GeV

(In)direct Constraints on Higgs Mass

- World top quark mass and W boson mass included, from LEP/TEVEWK working group:
 - $m_H = 87^{+35}_{-26}$ GeV
 - $m_H < 157$ GeV (95% CL)
 - $m_H < 186$ GeV (when LEP limit included)



LP09



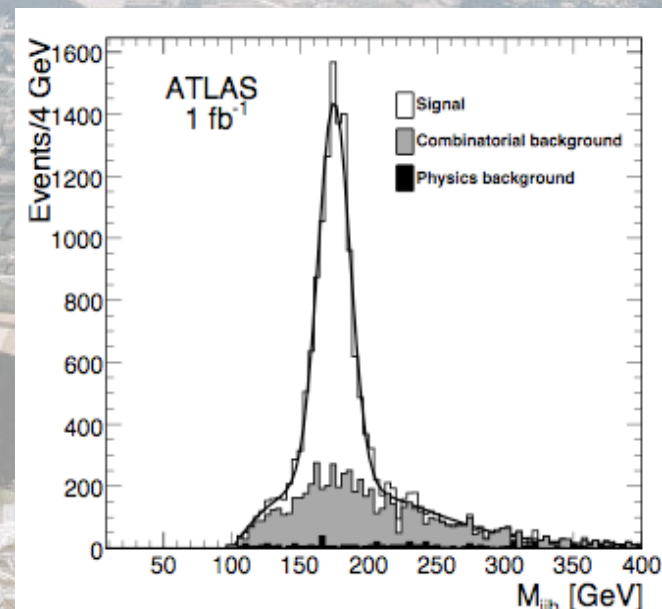
W Boson and Top Quark Mass at the LHC

■ W boson mass:

- Expectations using 15 pb⁻¹ and 14 TeV (ATLAS)
 - $m_T^W \sim 60 \text{ (stat)} \pm 114 \text{ (syst)} \text{ MeV}$
 - $p_T^l \sim 110 \text{ (stat)} \pm 230 \text{ (syst)} \text{ MeV}$
- Reaching Tevatron precision will require time

■ Top quark mass:

- Expect 2 GeV with 1fb⁻¹ and 14 TeV
 - Constraining the light JES, main uncertainty will come from b-JES
- With enough statistics the LHC experiments should be able to reach 1 GeV
 - Large datasets should provide good handles on systematic uncertainties



Top Quark Properties

Properties of the top quark

Searches in the top quark sample

Top Quark Properties

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: <http://pdg.lbl.gov>)



$$I(J^P) = 0(\frac{1}{2}^+)$$

$$\text{Charge} = \frac{2}{3} e \quad \text{Top} = +1$$



Mass $m = 174.2 \pm 3.3$ GeV ^[b] (direct observation of top events)
 Mass $m = 172.3^{+10.2}_{-7.6}$ GeV (Standard Model electroweak fit)

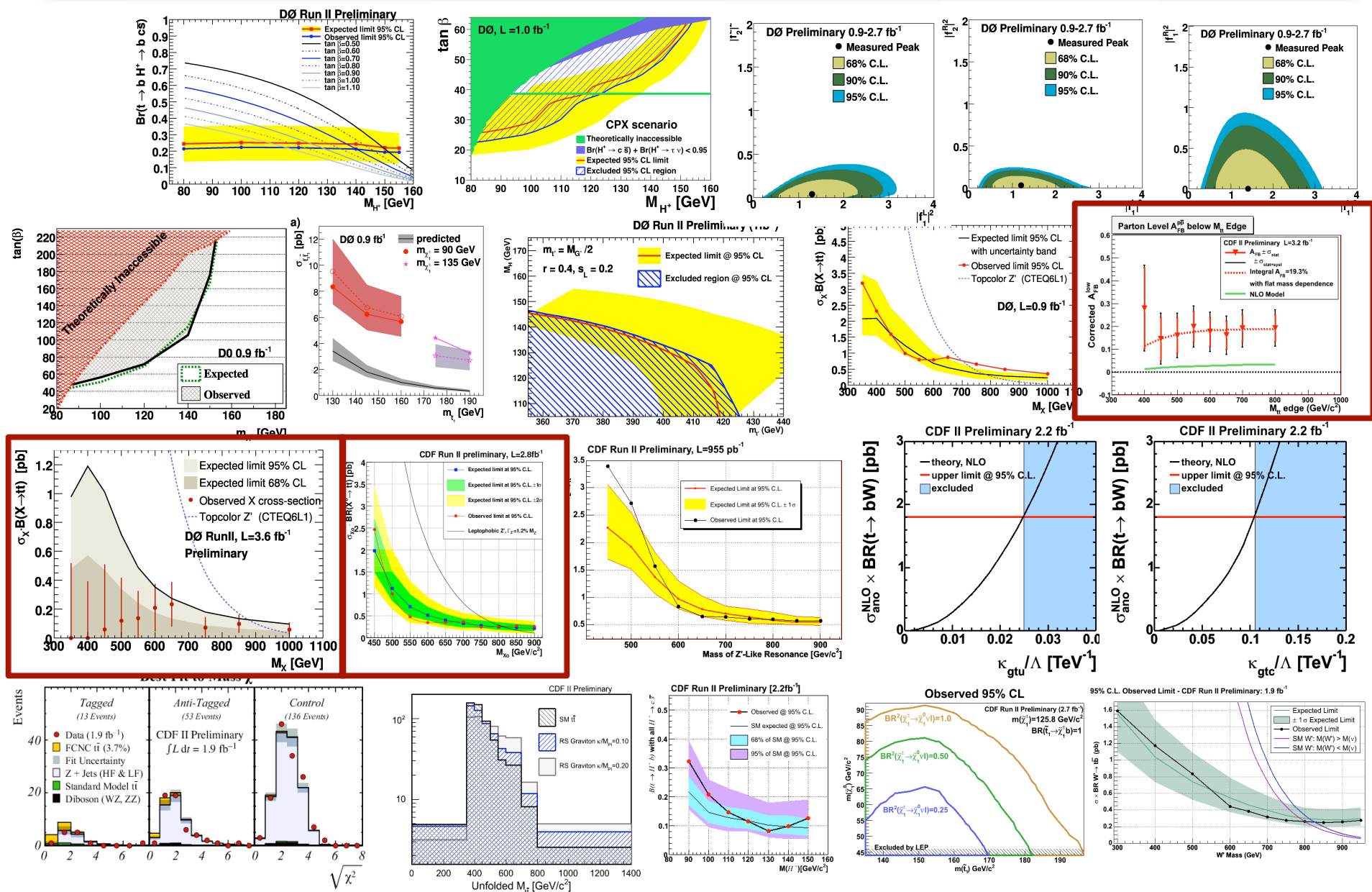
t DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$W q (q = b, s, d)$			—
$W b$			—
$\ell \nu_\ell$ anything	[c,d] (9.4 ± 2.4) %		—
$\tau \nu_\tau b$			—
$\gamma q (q=u,c)$	[e] < 5.9 $\times 10^{-3}$	95%	—
$\Delta T = 1$ weak neutral current (T1) modes			
$Z q (q=u,c)$	T1 [f] < 13.7 %	95%	—

The best evidence so far it is the SM top quark comes from the agreement of σ_{tt} with theoretical expectations but a priori there is no guarantee that this is the SM top

Top Quark Properties Summary

Property	Run II Measurement	SM prediction	Luminosity (fb ⁻¹)
m_t	CDF: $172.6 \pm 0.9(\text{stat}) \pm 1.2(\text{syst})$ GeV D0: $174.2 \pm 0.9(\text{stat}) \pm 1.5(\text{syst})$ GeV		4.3 3.6
$\sigma_{t\bar{t}} (@m_t=172.5 \text{ GeV})$ $\sigma_{t\bar{t}} (@m_t=170 \text{ GeV})$	CDF: $7.50 \pm 0.31 (\text{stat}) \pm 0.34 (\text{syst}) \pm 0.15 (\text{lumi})$ pb D0: $7.84^{+0.46}_{-0.45} (\text{stat})^{+0.66}_{-0.54} (\text{syst})^{+0.54}_{-0.46} (\text{lumi})$ pb	7.4 ± 0.6 pb 8.06 ± 0.6 pb	4.5 1
$\sigma_{\text{single top}} (@m_t=170 \text{ GeV})$	Tevatron: $2.76^{+0.58}_{-0.47} (\text{stat+syst})$	2.86 ± 0.8 pb	3.2-2.3
$ V_{tb} $	Tevatron: $0.91 \pm 0.08 (\text{stat+syst})$	1	3.2-2.3
$\sigma(\text{gg} \rightarrow t\bar{t}) / \sigma(\text{qq} \rightarrow t\bar{t})$	D0: $0.07 \pm 0.15 \pm 0.07 (\text{stat+syst})$	0.18	1
$m_t - m_{t\bar{t}}$	D0: 3.8 ± 3.7 GeV	0	1
$\sigma(t\bar{t} \rightarrow l\bar{l}) / \sigma(t\bar{t} \rightarrow l + \text{jets})$	D0: $0.86^{+0.19}_{-0.17} (\text{stat+syst})$	1	1
$\sigma(t\bar{t} \rightarrow \tau l) / \sigma(t\bar{t} \rightarrow l\bar{l} + l + \text{jets})$	D0: $0.97^{+0.32}_{-0.29} (\text{stat+syst})$	1	1
$\sigma_{t\bar{t} + \text{jets}} (@m_t=172.5 \text{ GeV})$	CDF: $1.6 \pm 0.2 (\text{stat}) \pm 0.5 (\text{syst})$	$1.79 \pm 0.16 \pm 0.31$ pb	4.1
$\mathcal{C}T_{\text{top}}$	CDF: $52.5 \mu\text{m}$ @ 95%C.L.	$10^{-10} \mu\text{m}$	0.3
T_{top}	CDF: < 13.1 GeV @ 95%C.L.	1.5 GeV	1
$\text{BR}(t \rightarrow Wb) / \text{BR}(t \rightarrow Wq)$	CDF: > 0.61 @ 95% C.L. D0: $0.97^{+0.09}_{-0.08} (\text{stat+syst})$	1	0.2 0.9
F_0	CDF: 0.62 ± 0.11 D0: $0.490 \pm 0.106 (\text{stat}) \pm 0.085 (\text{syst})$	0.7	2 2.7
F_+	CDF: -0.04 ± 0.05 D0: $0.110 \pm 0.059 (\text{stat}) \pm 0.052 (\text{syst})$	0.0	2 2.7
Charge	CDF: - 4/3 excluded with 87% C.L. D0: $4e/3$ excluded at 92% C.L.	2/3	1.5 0.37
Spin correlations	CDF: $\kappa = 0.32 + 0.55 - 0.78, -0.46 < \kappa < 0.87$ @ 68%C.L. D0: $\kappa = -0.17^{+0.65}_{-0.53} (\text{stat} + \text{syst})$	$0.78^{+0.027}_{-0.022}$	2.8 4.2
Charge asymmetry	CDF: $0.19 \pm 0.07(\text{stat}) \pm 0.02(\text{syst})$ % D0: $12 \pm 8 (\text{stat}) \pm 1 (\text{syst})$ %	0.05 ± 0.015	3.2 0.9

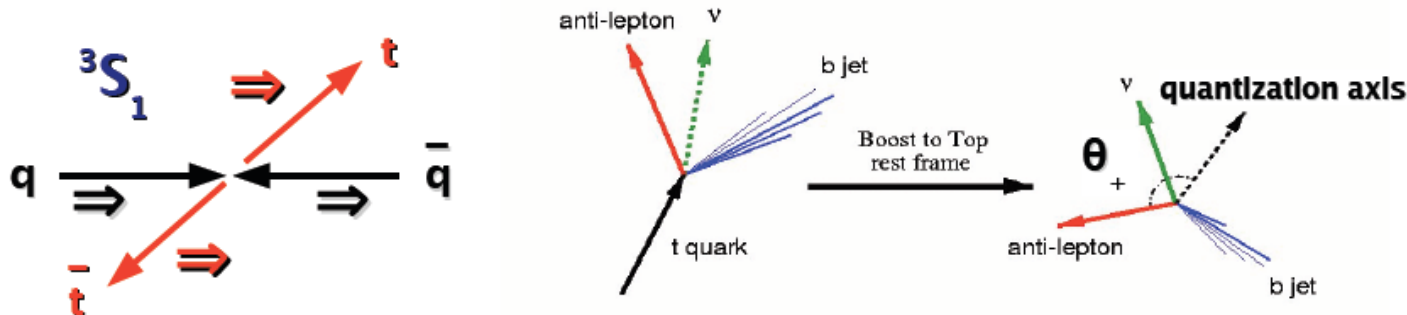
Searches in the Top Quark Sample



Top anti-Top Spin Correlations

Summer
09

- Only top quark decays before its spin flips
 - Information on of the spin carried by the decay products

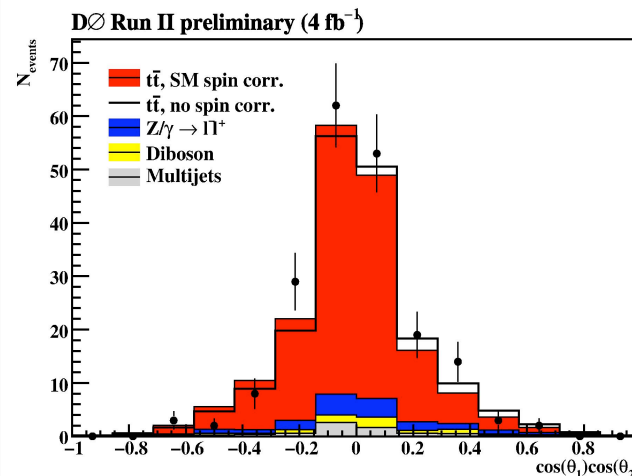
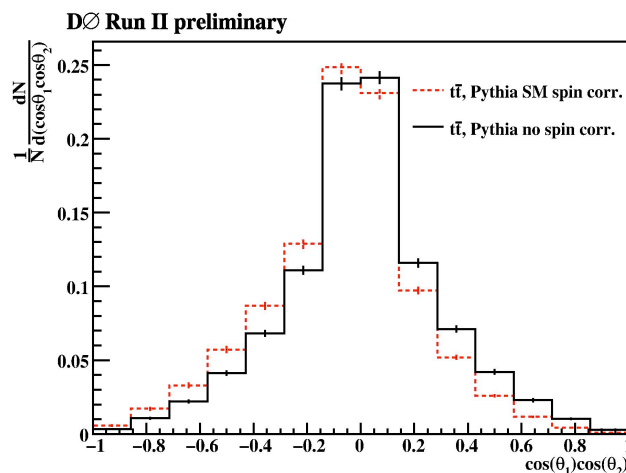


- Measurement can give an upper limit on lifetime, lower limit on V_{tb} and also limits beyond SM physics

$$\kappa = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- First results from Run II (dilepton channel)

SM predicts $\kappa = 0.78$



DØ (4 fb⁻¹):

$\kappa = -0.17^{+0.64}_{-0.53}$

Beam axis

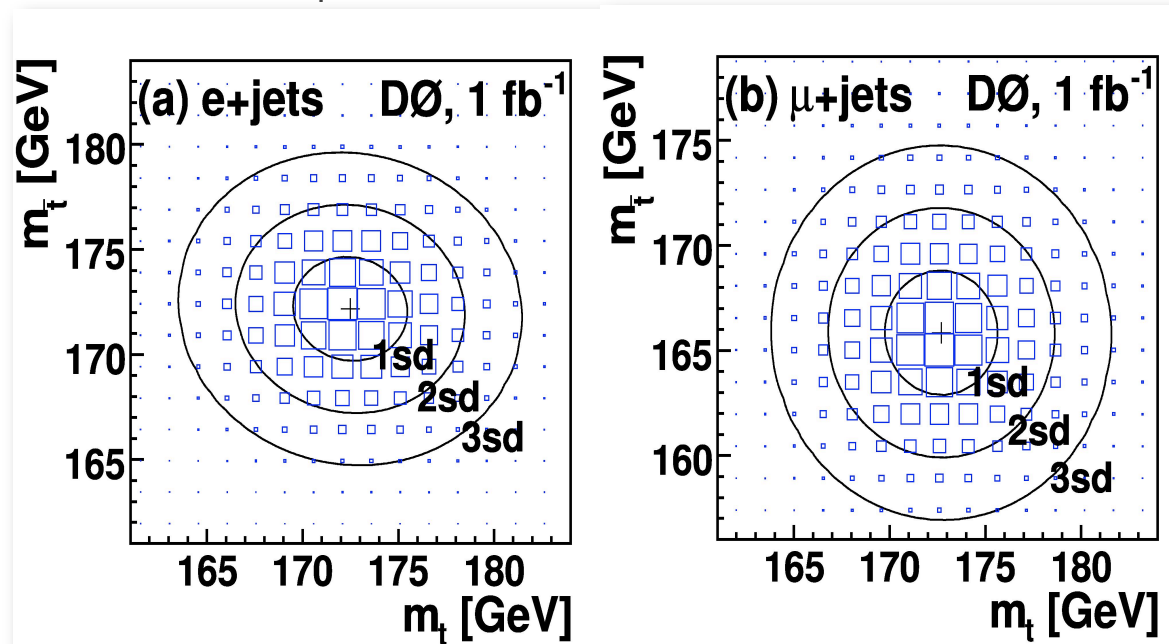
CDF (2.8 fb⁻¹):

$\kappa = 0.32^{+0.55}_{-0.78}$

Off-diagonal axis

Search for CPT Violation

- Measure mass difference between t and $tbar$
- No violations ever observed, but this is the first CPT measurement in the quark sector
- Releasing constraint on $m_t = m_{tbar}$, measured in lepton + jets events using matrix element technique



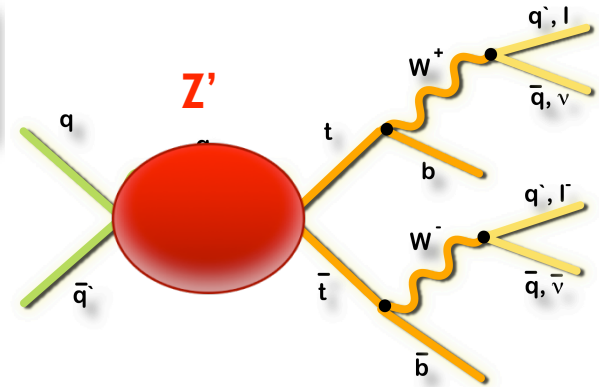
D0 (1 fb^{-1}):
 $\Delta m_t = 3.8 \pm 3.7 \text{ GeV}$



- Consistent with SM expectations

Searches in $t\bar{t}$ Production

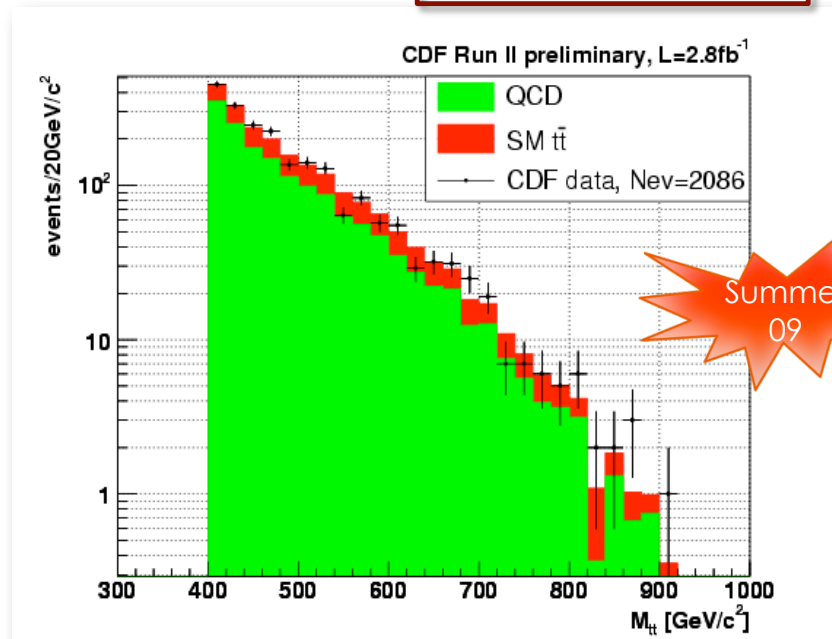
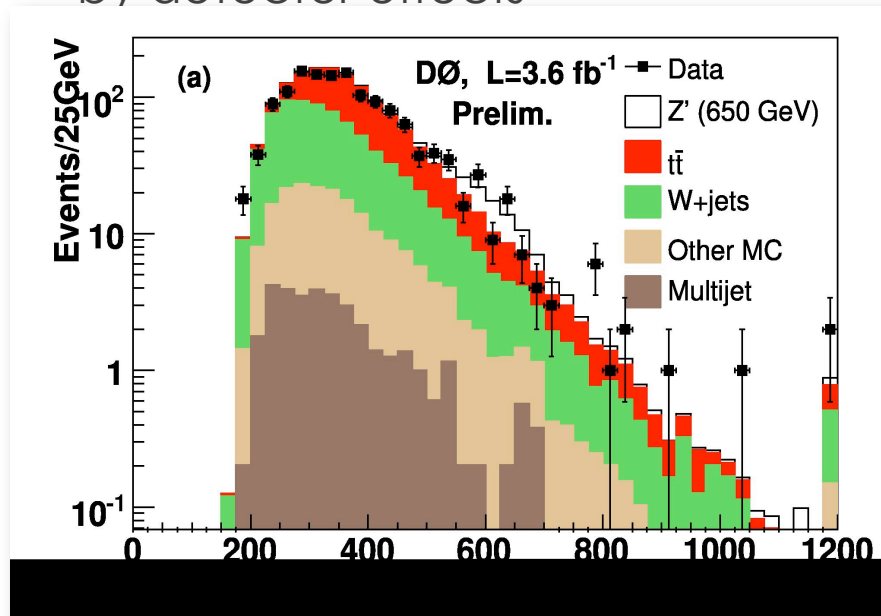
- No **resonance production** in $t\bar{t}$ system is expected in the standard model
- Some models predict **$t\bar{t}$ bound states**
 - Top color assisted technicolor predicts leptophobic Z' with strong 3rd generation coupling
- Experimental check: search for **bumps** in $t\bar{t}$ reconstructed mass spectrum
- Sufficiently narrow so that width is dominated by detector effects



Z' with 1.2% width:

D0 (3.6 fb^{-1}):
>820 GeV

CDF (2.8 fb^{-1}):
>805 GeV



Searches in $t\bar{t}$ Production

- Forward-backward asymmetry

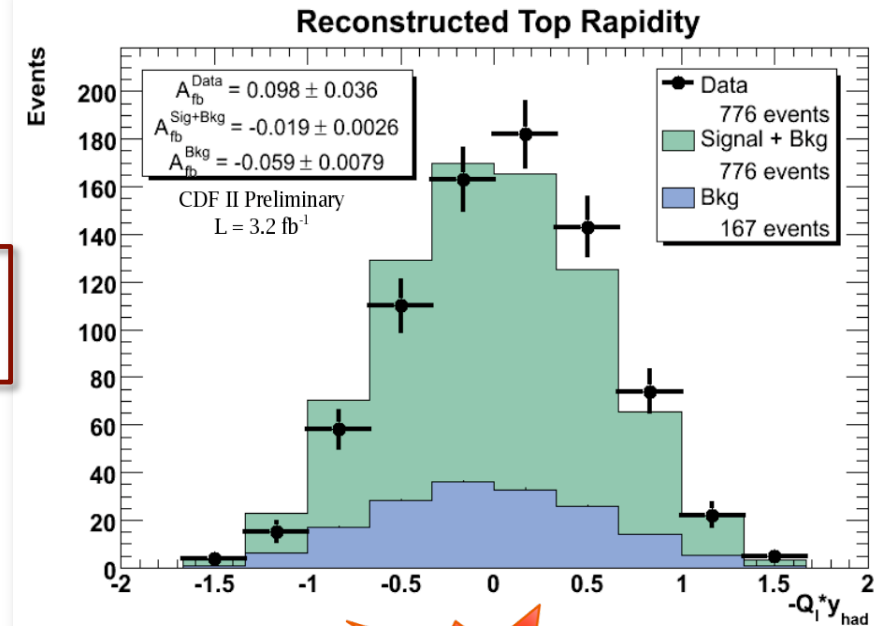
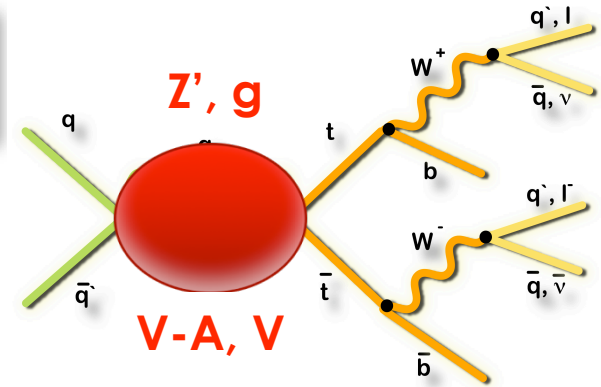
$$A_{fb} = \frac{F - B}{F + B}$$

- Parity violating new physics can appear as a large asymmetry
- Because the LHC is dominated by gg production this measurement will be far more difficult

CDF (3.2 fb⁻¹):

$A_{fb} = 0.193 \pm 0.065$ (stat) ± 0.024 (syst) %

- SM predicts at NLO $A_{fb} = 0.05 \pm 0.015$ %
- Agrees with SM within 2σ
- D0 result using 1 fb⁻¹:
 $A_{fb}^{\text{det}} = 0.12 \pm 0.08 \pm 0.01$ %



Summer
09

Summary and Conclusions

Summary and Conclusions

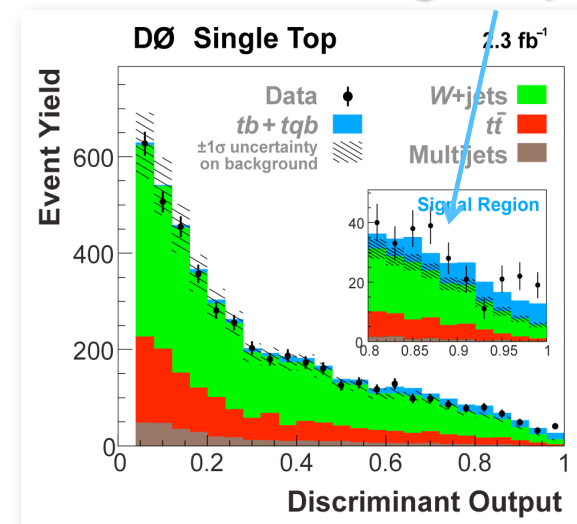
- Tevatron making **precision measurements** to help constrain SM
 - Examples shown: W charge asymmetry, $\sin^2 \theta_W$
- In the last year we have **expanded our experimental reach** on signatures
 - Confidence in our experimental tools while establishing challenging processes on our way to the Higgs boson (diboson, single top)
- Top quark cross section known to 6.5% (better than theory!)
- Top quark mass known to 0.7%
 - Tevatron should be able to reach 1 GeV
- W boson mass Tevatron combination better than LEP2 average!
 - Tevatron should be able to reach 20 GeV
- Top quark physics beginning to have sensitivity to unexpected in particle properties and in the data samples
- In the near future, LHC will rediscover top and use it as most likely the most important stepping stone to find new physics

Backup Slides

Single Top Quark: Results

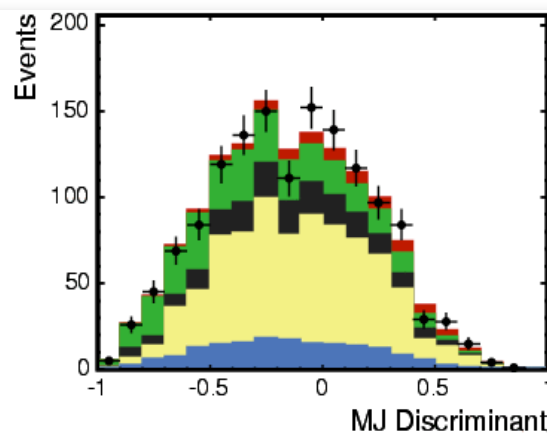
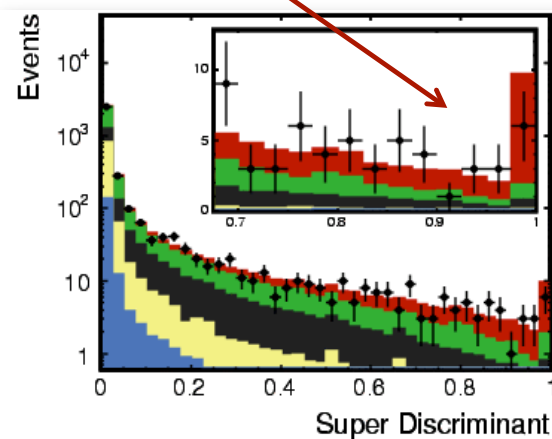
- Combine different multivariate analyses into one:
- D0 using 2.3 fb^{-1}
 - neural networks, matrix element, boosted decision trees
- CDF using 3.2 fb^{-1}
 - neural networks, matrix element, boosted decision trees, likelihood

Single top



Single top

Missing ET+jets selection:
Recover badly reconstructed e, μ : include τ

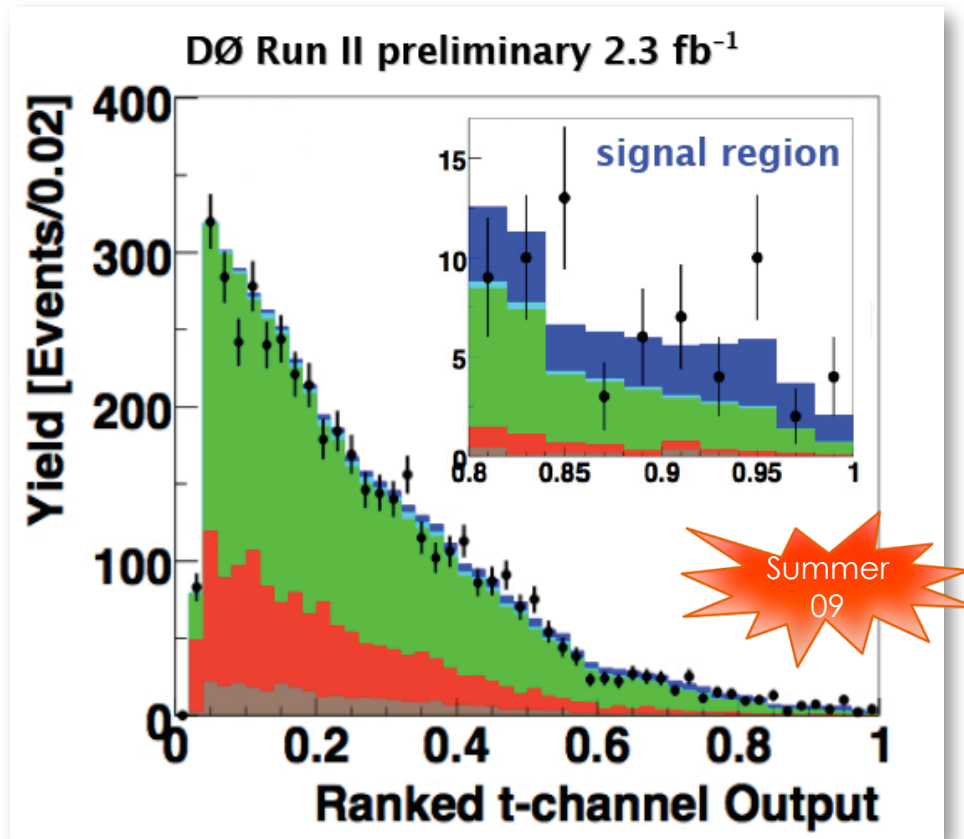


CDF Run II Preliminary, $L = 3.2 \text{ fb}^{-1}$

- Single Top
- W+HF
- $t\bar{t}$
- QCD+Mistag
- Other
- Data

Single Top Quark: t-channel

- Measure t-channel cross section by removing s/t channel constraint
 - Ratio could be changed due to additional quark generation, new heavy bosons, FCNC, anomalous quark couplings
- Measure t-channel and s-channel simultaneously



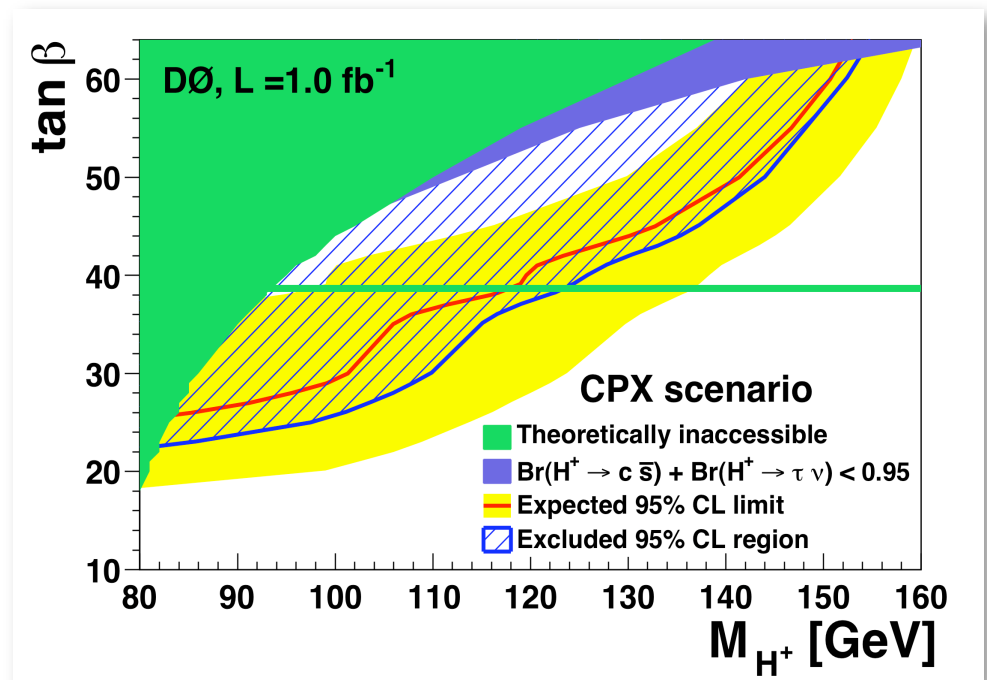
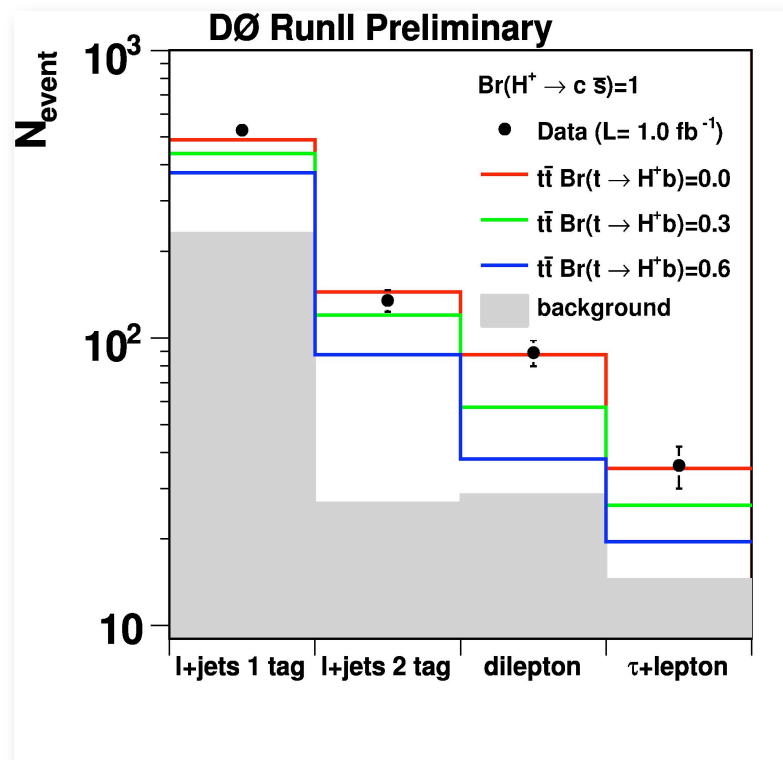
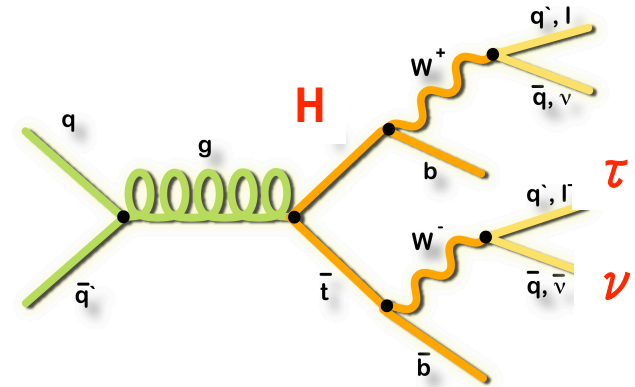
DØ (2.3 fb⁻¹):

$$\sigma_t(\text{t-channel}) = 3.14^{+0.94}_{-0.81} (\text{stat} + \text{syst}) \text{ pb}$$

First evidence with 4.8 σ

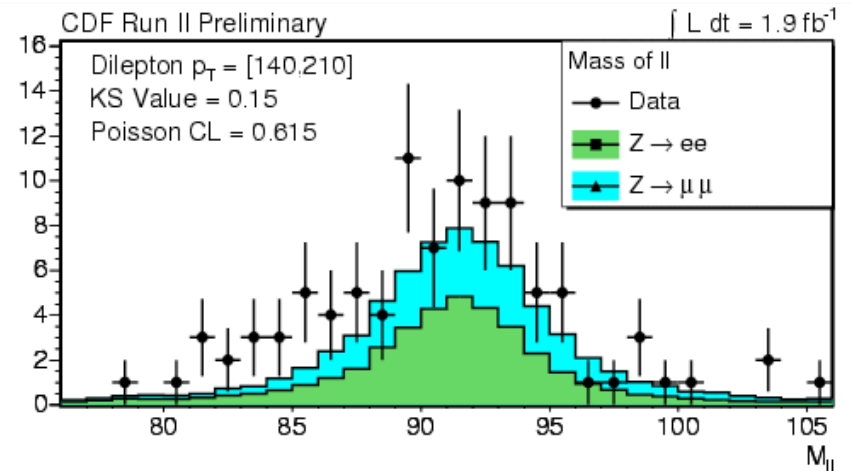
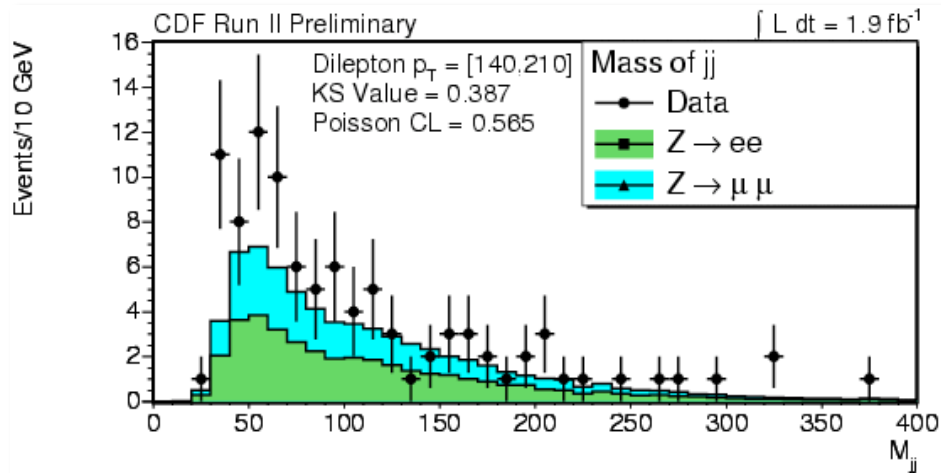
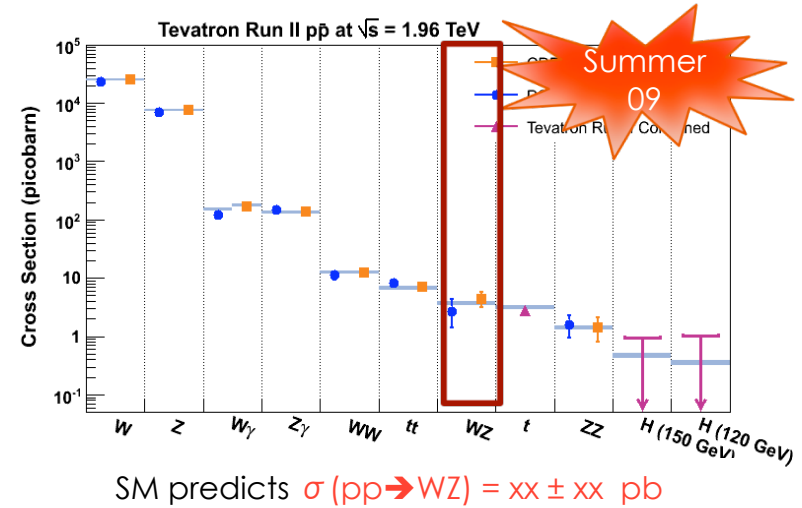
Searches in $t\bar{t}$ Decay

- Search for **charged Higgs** using e +jets, μ +jets, ee , $e\mu$, $\mu\mu$, τe and $\tau\mu$ final states from top quark pair production event
- Different **scenarios of possible H^\pm** where
 - decays purely hadronically into c and s quarks
 - decays into a τ lepton and a τ neutrino
 - both decays appear



WZ

- $WZ \rightarrow l \nu ll$ observed in 2007
 - TGC limits by D0 and CDF
- $WZ \rightarrow l \nu jj$ not yet observed at Tevatron
 - Could distinguish from WW via b-tagging
 - Higher cross section than low mass Higgs but softer (WH)
- $WZ \rightarrow jjll$ not yet observed at Tevatron
 - CDF calculates TGC limits using the leptonic (M_{ll}) and hadronic (M_{jj}) invariant masses
 - First **charged aTGC limits** in this channel



$t\bar{t}$ +jets Cross Section

- Important test of **perturbative QCD**
 - NLO effects play an important role in the calculation of the theoretical cross section
- Most top events at the **LHC** will be produced with additional jets
 - **Background for many new physics signals**
- Measurement using b-tagged events in the lepton plus jets channel
 - Data-driven background expectation
 - 2D likelihood simultaneously measure $t\bar{t}$ +jet and $t\bar{t}$ without jet cross sections.

CDF (4.1 fb⁻¹):

$$\sigma_{t\bar{t}+jets} = 1.6 \pm 0.2(\text{stat}) \pm 0.5(\text{syst}) \text{ pb}$$

SM predicts $\sigma_{t\bar{t}+jets} = 1.79^{+0.16}_{-0.31} \text{ pb}$

